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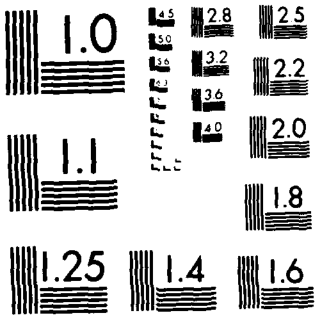

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IN-FLIGHT INVESTIGATION OF LONGITUDINAL FLYING QUALITIES CRITERIA

by
David B. Glade II
and
Michael E. Murphy

Princeton University
Flight Research Laboratory
Department of Mechanical and Aerospace Engineering
Princeton, New Jersey 08544

February, 1983

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Flight tests were conducted to aid the development of new longitudinal flying qualities criteria and to investigate some of the implications of equivalent system analysis, in which an aircraft's high-order dynamics are modelled by a low-order system. These tests were flown by U.S. Navy test pilots in Princeton University's Variable-Response Research Aircraft (VRA), a fly-by-wire, in-flight simulator. Both analog and digital

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(microprocessor-based) systems were used for closed-loop control. Tests of 22 dynamic configurations evaluated by 5 pilots are reported, with emphasis on tasks representative of approach and landing on an aircraft carrier. A standard carrier landing mirror provided pilot cues, and all flights were evaluated from the long approach through touchdown.

Conclusions regarding flying qualities are based on a limited number of flights. Ratings of conventional configurations generally indicated a compatibility with present flying qualities boundaries based upon the control anticipation parameter (CAP), but the latter do not adequately predict pilot ratings for short period natural frequencies of 2 rad/sec and less. CAP tended to confirm landing task ratings, but it did not confirm ratings based solely on pitch response. "Close" ratings followed the trends of "Approach" ratings, though they were greater for smaller values of $1/T_{\theta_2}$. Time delays of 0.16 sec or more consistently degraded ratings, and the combination of increased delay (0.26 sec) with low lift-curve slope was prone to cause pilot-induced oscillations.

The ratings of equivalent systems based on fixed L_α correlated more closely with the high-order system ratings than did the ratings of equivalent systems based on free L_α for the landing approach task. Equivalent systems were matched to the high-order systems using pitch rate transfer function response only, and it is suggested that fixed L_α matching more closely approximates simultaneous matching of both pitch rate and normal acceleration response.

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DEFINITIONS

SYMBOLS

A	Generic gain	
E	Elevator position	deg
e	Base of natural logarithm	2.7183...
G	Equivalent system gain	
g	Gravitational constant	32.2 ft/sec^2
K	Generic gain	
L_α/V	Vertical damping derivative	sec^{-2}
M	Equivalent system mismatch	
M_α	Angle of attack static stability derivative	sec^{-2}
M_q	Pitch damping derivative	sec^{-1}
n_z	normal acceleration	g
q	Pitch rate	rad/sec
S	Longitudinal stick position	deg
s	Laplace variable	
T	Digital sampling time	sec
T_{θ_2}	Short period numerator time constant	sec
V	Velocity	ft/sec or kt
α	Angle of attack	rad or deg
θ	Pitch angle	rad or deg
Φ	Phase angle	deg
ζ_e	Equivalent damping ratio	

ζ_{sp}	Short period damping ratio	
ω_e	Equivalent frequency	rad/sec
ω_{sp}	Short period natural frequency	rad/sec

ABBREVIATIONS

CAP	Control Anticipation Parameter
CAP'	Attenuated Control Anticipation Parameter
DFCS	Digital Flight Control System
FCCU	Flight Control Computer Unit
FCLP	Field Carrier Landing Practice (mirror)
HQR	Handling Qualities Rating
HOS	Higher-Order System
ICP	Initial Cyclic Parameter
LOES	Low-Order Equivalent System
Micro-DFCS	Microcomputer-based Digital Flight Control System
Mil Spec	MIL-F-8785, Military Specification, Flying Qualities for Piloted Airplanes
pCAS	Pascal Command Augmentation System
PDM	Pulse Duration Modulation
PIO	Pilot-Induced Oscillation
SBC	Single-Board Computer
TM	Telemetry Monitoring system
TRP	Time Response Parameter
VRA	Variable-Response Research Aircraft

NOTATION

$[\zeta, \omega]$	$s^2 + 2\zeta\omega s + \omega^2$
(σ)	$s + \sigma$

(s)	Laplace operator
ss	Steady state
nd	Non-dimensional

Chapter I

INTRODUCTION

1.1 A BRIEF HISTORY OF FLYING QUALITIES

Ever since the dawn of powered flight, aircraft designers have been interested in assuring that their aircraft will be stable and controllable. Stability of an aircraft is its tendency to resist changes in the magnitude and direction of its velocity vector. Control is the ability to change the velocity vector in order to steer an arbitrary flight path. Devices which alter an airframe's stability and control characteristics are known as augmentation devices. There are trade-offs, in designing an aircraft, between degrees of stability and degrees of controllability. Those characteristics of stability and controllability are collectively known as flying qualities.

Early aircraft were relatively stable and simple to control. Autopilots were developed primarily to stabilize the aircraft in straight-and-level flight. The first suggestions for flying qualities appeared in the 1930s, and the first formal set of requirements appeared in 1943. Better technology and the quest for ever higher performance, however, has led to greater demands on aircraft control systems, due to reduced damping, control boost systems, and expanded flight envelopes. This led to flying qualities requirements based, as they are today, on pilot opinions, and related to a few, well-defined and recognizable modes of aircraft motion. These modes are characteristic of aircraft with no augmentation; as a result, the flying qualities requirements were specified in terms of natural frequencies and damping ratios [1].

More recently, high performance aircraft have been built with more extensive use of augmentation devices in order to counter significant structural modes and relaxed static stability. These augmentation devices themselves add significant effects to control response, to the point that the modes of the classic unaugmented aircraft are often no longer recognizable [2]. Furthermore, transfer functions of augmented aircraft may be of very high order, requiring alternate flying qualities criteria.

The problem of flying qualities of higher order systems is the theme of this report. Several schemes have been suggested for dealing with this problem, including the Equivalent Systems technique [3-9]. This is a method of matching the gain and phase characteristics of a higher order system to those of a lower order system. The low order system derived through this method, however, is not unique. Several parameters used in the matching process may be altered, during different matches, to give different answers. The significance of the differences is unclear. The experimental program described in this report is an attempt to clarify the effect of variations in Equivalent Systems parameters on flying qualities parameters and on pilot ratings.

1.2 ORGANIZATION OF REPORT

Chapter 2 is an introduction to longitudinal flying qualities. It briefly lists applicable sections of the Military Specifications, including a short discussion of the Control Anticipation Parameter. It presents inadequacies in describing criteria for higher-order, augmented systems. The chapter continues with descriptions of alternate proposals for longitudinal flying qualities criteria.

Chapter 3 describes the flight tests which were designed to study the nuances of the equivalent systems technique. Included are descriptions of the models used. It describes the equipment used in the aircraft, and the development of the software used in the flight control system.

Chapter 4 lists procedures followed in the flight tests, and it presents analysis of the results of the tests.

Chapter 5 presents conclusions that can be drawn from the pilot opinion ratings and from the commentary on the flights, and it presents recommendations for further work.

The appendices include technical information on the aircraft and computer systems and software. They also include the pilot comment cards and data from the flight tests.

Chapter II

FUNDAMENTALS OF FLYING QUALITIES CRITERIA

This chapter describes the standard method of subjectively rating aircraft, the current objective flying qualities requirements, and proposals for new objective requirements. As noted in the introduction, flying qualities are characteristics of aircraft which describe their stability and control qualities. The purpose of specifying certain flying qualities is to insure that pilots can fly aircraft safely and with a minimum of effort. In order to relate an aircraft's motions to how well a pilot can fly that aircraft, there must be a method for pilots to rate aircraft, and a method of specifying the aircraft motion. A concise, repeatable method for rating aircraft has been in use since 1969. It is described briefly in the first part of the chapter. Specifying the motion is a difficult task, as indicated in the introduction. It is the subject of the rest of this chapter.

2.1 PILOT OPINION RATING

The current standard method of rating aircraft was developed by G. E. Cooper and R. P. Harper, Jr. [10]. In this method, pilot opinions are rated on a scale of 1 to 10, with a rating of 1 indicating excellent flying qualities, and 10 showing that, at some point, the aircraft is uncontrollable. Cooper and Harper specified in their work the decision process by which the rating is decided. This method has been shown to yield reasonably consistent ratings among different test pilots. The rating scale and the decision process are shown in Fig. 2.1.

HANDLING QUALITIES RATING SCALE

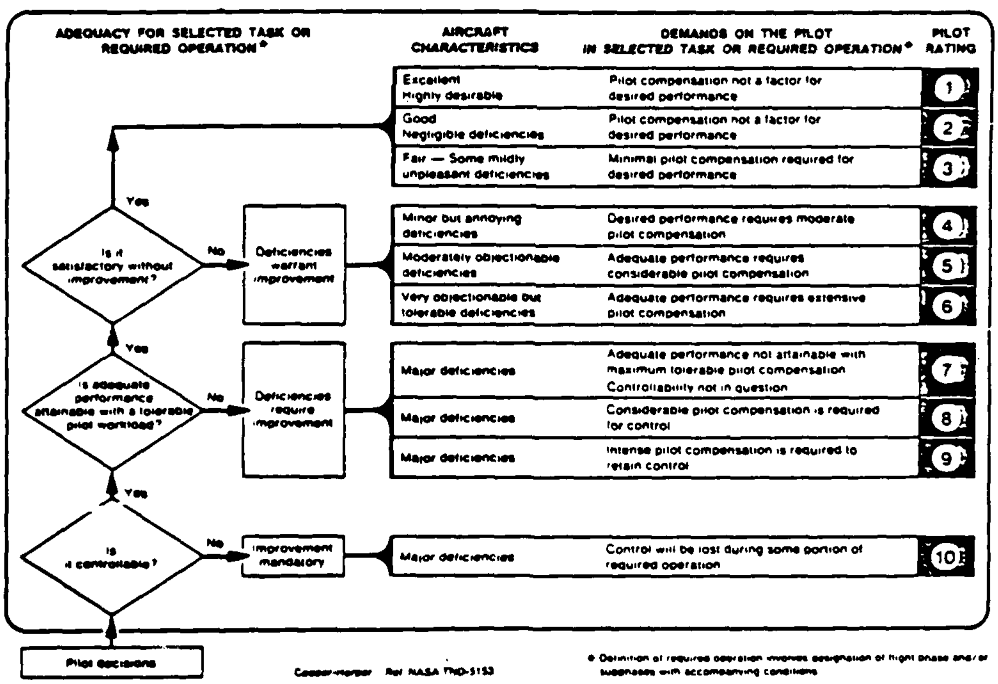

Figure 2.1. Cooper-Harper Pilot Opinion Rating Scale

2.2 MILITARY SPECIFICATIONS

A discussion of flying qualities would be incomplete without a discussion of the Military Specifications. The Mil Specs are intended to insure that new aircraft will not have bad flying qualities by specifying characteristics that have, in the past, led to good pilot opinion ratings of aircraft. Even though the characteristics used in the current Mil Specs may not be valid for highly augmented aircraft, they provide a starting point for examining flying qualities criteria.

The current military specification, MIL-F-8785C, published in November, 1980, specify four classes of airplanes [1]. The class which is receiving the greatest attention regarding higher order systems (HOS) is Class IV, which includes:

Class IV, High maneuverability airplanes

- Fighter/interceptor
- Attack
- Tactical reconnaissance
- Observation
- Trainer for Class IV

Further, the specification specifies three flight phase categories. They are, Category A--Those nonterminal Flight Phases that require rapid maneuvering, precise tracking, or precise flight-path control. Included in this Category are:

a. Air-to-air combat (CO)

b. Ground attack (GA)

c. Weapon delivery/launch (WD)

d. Aerial recovery (AR)

e. Reconnaissance (RC)

f. In-flight refueling (receiver) (RR)

g. Terrain following (TF)

h. Antisubmarine search (AS)

i. Close formation flying (FF)

Category B--Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in this Category are:

a. Climb (CL)

b. Cruise (CR)

c. Loiter (LO)

d. In-flight refueling (tanker) (RT)

e. Descent (D)

f. Emergency descent (ED)

g. Emergency Deceleration (DE)

h. Aerial delivery (AD)

Category C--Terminal Flight Phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this Category are:

a. Takeoff (TO)

b. Catapult takeoff (CT)

c. Approach (PA)

d. Wave-off/go-around (WO)

e. Landing (L)

The specifications in MIL-F-8785C are presented in terms of levels of flying qualities, which relate to pilot opinions of flying qualities. The three levels are:

Level 1 Flying qualities clearly adequate for the mission Flight Phase

Level 2 Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists

Level 3 Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.

MIL-F-8785C does not mention Pilot Opinion Ratings. In other flying qualities literature, however, the flying qualities levels generally are related to pilot opinion ratings as follows:

Level	POR
1	1,2,3
2	4,5,6
3	7,8,9

POR 10, since it indicates an uncontrollable aircraft, does not relate to any of the flying qualities levels.

Longitudinal handling qualities have been chosen for study. The longitudinal requirements are covered by Section 3.2.2 of MIL-F-8785C. The classic equation describing such longitudinal motions is the transfer function of pitch response to pilot input transfer function, of the form:

$$\frac{\Delta q\ (s)}{\Delta \delta E(s)} = \frac{K_\theta \ (s + L_\alpha/V)}{(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)} \qquad (2\text{-}1)$$

Short period frequency and acceleration sensitivity are required to be within the limits shown in Fig. 2.2, 2.3, and 2.4. These requirements are based on the Control Anticipation Parameter (CAP), which is explained below. Short period damping is required to be within the limits shown in Table 2.1.

In addition, sustained residual oscillations must not interfere with the pilot's ability to perform the tasks required by the mission: "For Levels 1 and 2, oscillations in

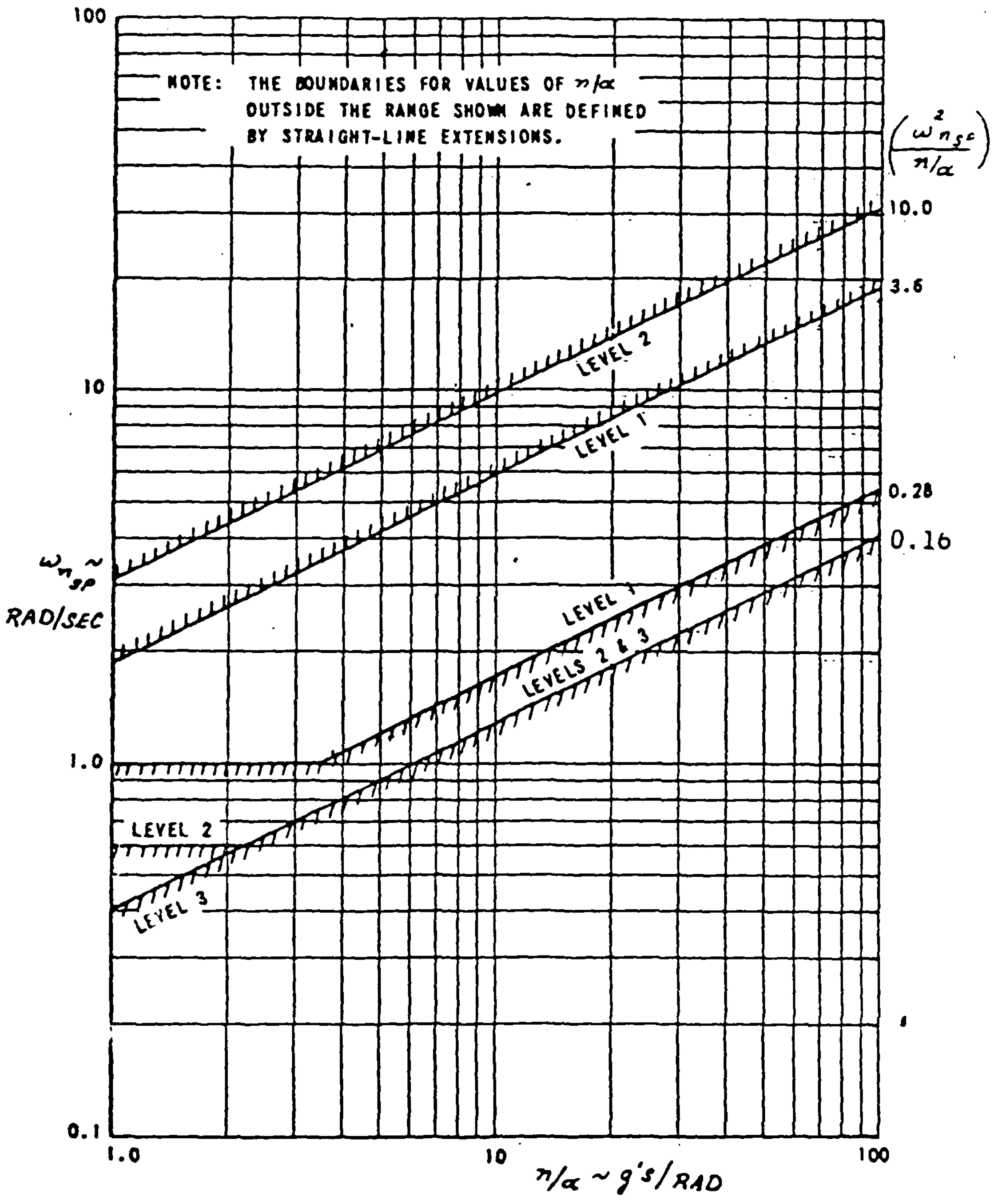

Figure 2.2. Short Period Frequency Boundaries, Category A, from Ref. 1.

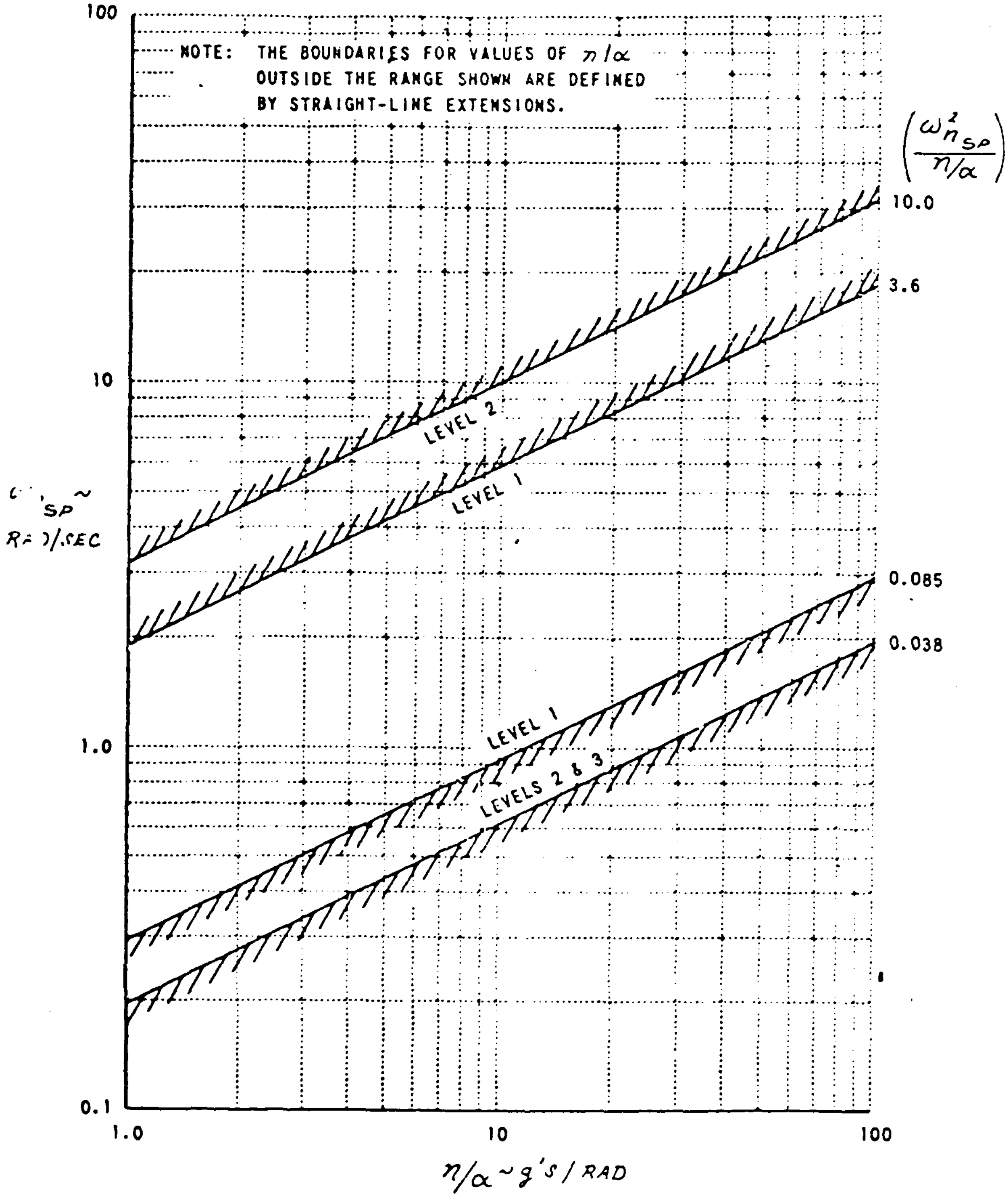

Figure 2.3. Short Period Frequency Boundaries, Category B, from Ref. 1.

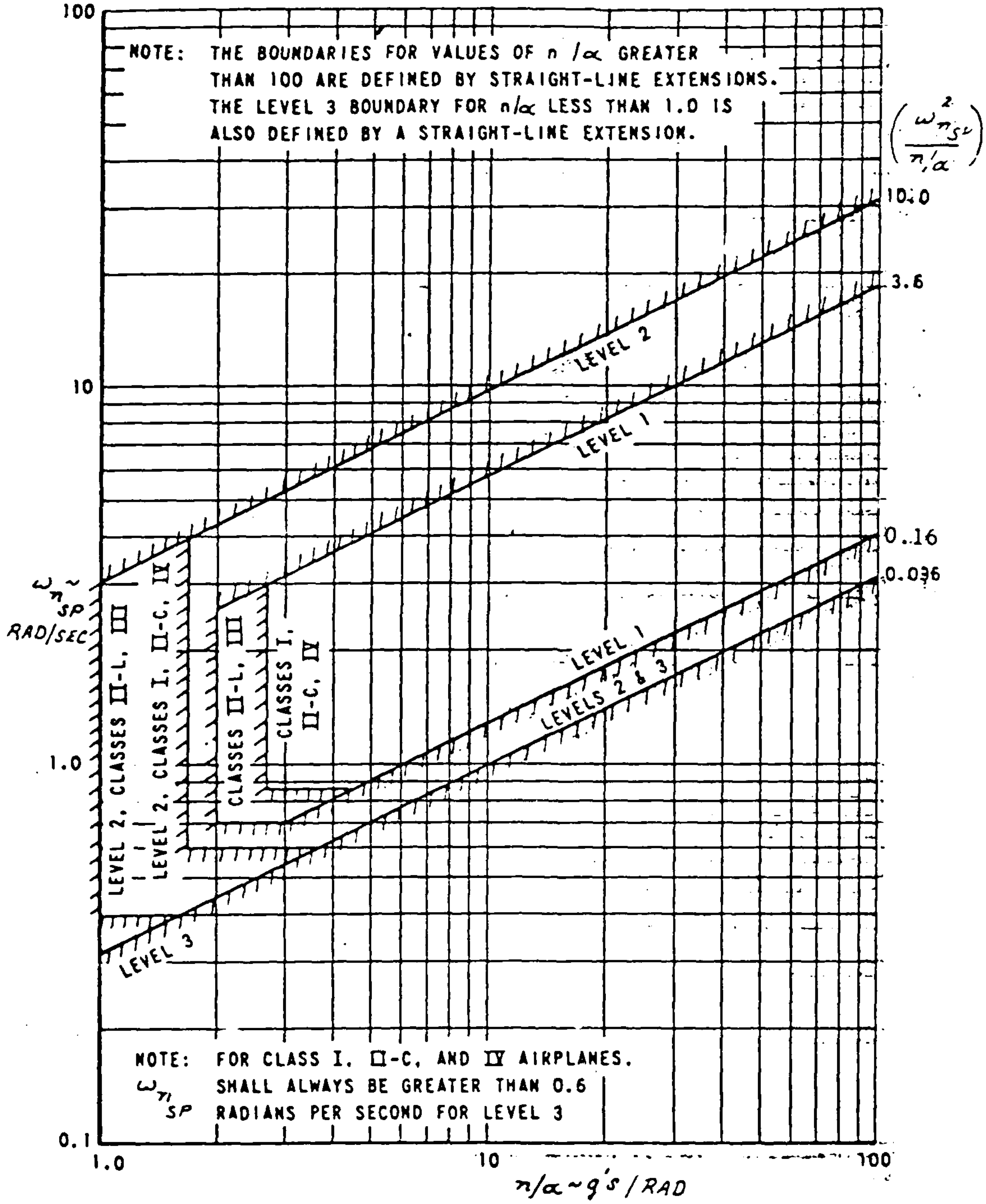

Figure 2.4. Short Period Frequency Boundaries, Category C, from Ref. 1.

TABLE 2.1

Short-Period Damping Ratio Limits

Category A and C Flight Phases

Level	Minimum	Maximum
1	0.35	1.30
2	0.25	2.00
3	0.15	-

normal acceleration at the pilot's station greater than $\pm 0.05g$ will be considered excessive for any Flight Phase, as will pitch attitude oscillations greater than ± 3 mils for Category A Flight Phases requiring precise control of attitude" [1]. Also, stick force gradients are specified: the satisfactory level is from 3.5 to 9.3 lb/g, assuming a limit load factor of 7g.

2.3 CONTROL ANTICIPATION PARAMETER

The Control Anticipation Parameter, which forms the basis for the longitudinal, short period frequency requirements, was developed by Bihrle [11]. It is based on the premise that the ratio of initial pitch response to the quasi-steady-state normal acceleration is important to the pilot. It is defined as:

$$CAP = \frac{\ddot{\theta}(t = 0^+)}{n_{zss}} = \frac{\Delta q^*}{\Delta n_z^* \Delta t_q^*} \qquad (2\text{-}2)$$

Using the short-period approximation, it is alternately defined as:

$$CAP = \frac{\omega_{sp}^2}{n/\alpha} = \frac{-(M_\alpha + M_q L_\alpha/V)}{(L_\alpha/g)} \qquad (2-3)$$

The alternate definition is derived from the first using certain simplifying assumptions regarding the pitch response of the aircraft. CAP has also been shown to be proportional to static margin [12]. The boundaries of the flying qualities levels are defined by lines of constant CAP (see Fig. 2.5). The lower limit on natural frequency assures that both attitude and path response will be "fast enough". The lower bounds on n/α are to restrict the lag between pitch and flight path response in landing approach [13].

The second definition of Control Anticipation Parameter (eq. 2-3) normally is not effective in characterizing higher order systems because the initial pitch response of such systems often is delayed by control system dynamics, including digital delays, structural notch filters, and other shaping. As a consequence, there is increased interest in time-based definitions of CAP, e.g., eq. 2-2. For example, Reference 3 suggests using $\ddot{\theta}_{max}$ rather than $\ddot{\theta}(0)$ in eq. 2-2.

2.4 EQUIVALENT SYSTEMS

The desire to retain the present, familiar flying qualities requirements and to have a simple method for evaluating complex, highly augmented aircraft led to the development of the equivalent systems technique. The premise of equivalent systems is that the response to pilot input of a Higher Order System (HOS) can be approximated by a Low Order Equivalent System (LOES), which is characterized by a natural frequency, damping ratio, and a time delay. The time delay approximates the increased phase lag of the HOS. The transfer function of the LOES is of the form:

$$\frac{\Delta q(s)}{\Delta \delta E(s)} = \frac{K_\theta \, (s + 1/T_{\theta 2}) \, e^{-\tau s}}{(s^2 + 2\zeta_e \, \omega_e \, s + \omega_e^2)} \tag{2-4}$$

Hodgkinson, et al. [4] developed a numerical frequency domain matching technique which implements a direct Rosenbrock digital search algorithm that matches the response of the LOES to that of the HOS. This is done by minimizing the sums of the squares of the differences in gain and phase angle of the two systems, at discrete frequencies, according to the following equation:

$$M = 20/n \sum ((G_{HOS} - G_{LOES})^2 + .01745(\phi_{HOS} - \phi_{LOES})^2) \tag{2-5}$$

where G = gain in dB, and ϕ = phase angle in degrees. The match is done at n discrete frequencies throughout the pilot's frequency range of interest, generally .1 to 10 rad/sec. This procedure is similar to minimizing the sum-of-squares error of the Bode plots of the HOS and LOES. In the search algorithm, the gain, damping ratio, frequency, and time delay are allowed to vary. The numerator term, $1/T_{\theta_2}$, may be fixed or may be allowed to vary.

The equivalent systems technique has some drawbacks, including lack of quidance about acceptable mismatch and ambiguity about whether L_α should be fixed or free. Hodgkinson, et al. suggest that mismatches can be judged subjectively, with mismatches of less than 10 generally being acceptable; however, they and others present evidence to suggest that pilots cannot detect differences for mismatches as high as 200 [5-7]. The question of whether L_α should be fixed or free is perhaps a more important problem, though, and it is the central question of this research. MIL-F-8785C acknowledges equivalent systems, but gives no guidance on whether the numerator term should be fixed or free. Reference 12 shows that there are substantial differences in equivalent frequency, damping, and time delay between the cases of numerator time constant fixed or free. The inverse time constant, $1/T_{\theta_2}$, can take very large or very small values when the high order system contains additional roots in the frequency range of interest. This could reflect large differences in the attitude responses of the fixed vs free models. Reference 8 states that freeing the time constant can produce L_α values as high as 600% of the aircraft value of L_α, but this provides a better match than the fixed values.

This effectively improves mid-frequency matching, but it could be interpreted as a higher n_z/α [5]. However, such "galloping" values of the time constant are clearly unrealistic when related to the aircraft lift curve slope. It has been suggested that the time constant is related to the lag between the attitude and path response of the aircraft. This implies that the proper technique is to match the attitude rate (q) and path responses (n_z) simultaneously. This method reduces the variation in L_α but increases the pitch rate transfer function mismatch. If, however, mismatches as high as 200 are indeed acceptable, it might be expected that numerator values from fixed, free, and simultaneous matches all would be valid. Moreover, the effects of the matching techniques on pilot opinion ratings are unclear. The effect of time delay on pilot opinion is another area of concern. One objective of this report is to gather more data in order to find maximum unnoticeable delay and the relationship of delay to pilot rating.

Some researchers believe that identifying a single mode from a higher order system is inadequate. However, others believe that Equivalent System models have sufficient parameters to deal with higher order systems [12]. One issue that is clear, however, is that in-flight investigation is required in order to clarify such questions. The program described in this report is an attempt to answer a few of them.

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Chapter III

FLIGHT TEST PROGRAM DEVELOPMENT

The flight test program that is described here was initiated to study the effects of higher order, augmented aircraft dynamics on pilot opinions of flying qualities. Specifically, possible ambiguities in the Equivalent Systems technique were investigated, and effects of time delay on pilot opinions ratings were determined. In terms of the former, one goal was to clarify whether the low order transfer function numerator, $1/T_{\theta_2}$, should be fixed at the aircraft value or allowed to vary during the curve-fitting procedure. The ability of Princeton's Variable-Stability Research Aircraft (VRA) to model the dynamic response of other aircraft, both with and without higher order augmentation effects, was ideal for this research. In addition, the data from this evaluation should prove useful in examining alternative proposals for flying qualities criteria.

3.1 FLIGHT TEST PLAN

The intent of the flight test program was to simulate Class IV aircraft in Category C flight conditions. More specifically, the configurations should simulate generic Navy fighter/attack aircraft in carrier approach and landing.

3.1.1 Matrix of Test Points

The test points were selected to compare the flying qualities of unaugmented aircraft with those of the augmented aircraft and their equivalents. Seven basic, unaugmented configurations were chosen, six of which lie within the Level 1 flying qualities boundaries, as shown in Fig. 3.1. These base configurations were implemented by an implicit model-matching technique using the analog flight control system of the VRA. The basic aircraft model is a fourth order differential equation:

$$\Delta\dot{\underline{x}} = \begin{bmatrix} -TD_V & -g & 0 & -D_\alpha \\ L_V/V_o & 0 & 0 & L_\alpha/V_o \\ (M_V-\frac{M_{\dot\alpha}L}{V_o}V) & 0 & (M_{\dot\alpha}+M_q) & (M_\alpha-\frac{M_{\dot\alpha}L_\alpha}{V_o}) \\ -L_V/V_o & 0 & 1 & -L_\alpha/V_o \end{bmatrix} \Delta\underline{x}$$

$$+ \begin{bmatrix} 0 & D_{\delta T} & 0 \\ L_{\delta E}/V_o & 0 & L_{\delta F}/V_o \\ (M_{\delta E}-\frac{M_{\dot\alpha}L}{V_o}\delta E) & 0 & -\frac{M_{\dot\alpha}L}{V_o}\delta F \\ -L_{\delta E}/V_o & 0 & -L_{\delta F}/V_o \end{bmatrix} \Delta\underline{u} \qquad (3\text{-}1)$$

where $\underline{x} = [\ V \quad \gamma \quad q \quad \alpha\ ]^T$ and $\underline{u} = [\ \delta E \quad \delta T \quad \delta F\ ]$. For simplicity, M_q, M_α, and L_α were the only derivatives altered from the basic values of the VRA. VRA values for the other derivatives are: $TD_V = .16$, $D_\alpha = 20$, $L_V/V_o = .0042$, $M_V = 0$, $M_{\dot\alpha} = -.88$, $D_{\delta T} = .509$, $L_{\delta E}/V_o = .089$, $L_{\delta F}/V_o = .266$, and $M_{\delta E} = -9.9$. M_q, M_α, and L_α values for the base configurations are listed in Table 3.1.

Prefilters were added to three of the base configurations, and the equivalent second-order models of these configurations were determined. In addition, three values of pure time delay were added to two of the base configurations.

TABLE 3.1

Aerodynamic Derivatives of Base Configurations

Config.	L_α/V	M_α	M_q
01	.71	-1.15	+.19
02	.71	-3.14	-1.17
03	.71	-7.15	-2.61
04	.71	-21.16	-5.41
05	1.6	-3.06	-.92
06	1.6	-3.49	-.32
07	1.6	-6.25	-1.72

The prefilters and time delays were implemented on the micro-computer-based Digital Flight Control System (micro-DFCS) of the VRA. The complete set of configurations is listed in Table 3.2; their transfer functions (neglecting the phugoid mode) are shown in Table 3.3.

The prefilters which were used to augment the base configurations are simple, first-order, low-pass filters, applied to the pilot's control stick output,

$$\frac{\Delta\delta E(s)}{\Delta\delta S(s)} = \frac{A(1/\tau)}{(s + 1/\tau)} \qquad (3\text{-}2)$$

where $\Delta\delta E(s)$ represents the elevator, $\Delta\delta S(s)$ represents the longitudinal stick position, and A is the stick gain. In state-space notation, this becomes:

$$\Delta\delta\dot{E} = -(1/\tau)\Delta\delta E + A(1/\tau)\,\Delta\delta S(s) \qquad (3\text{-}3)$$

The discrete-time model is:

$$\Delta\delta E_{K+1} = e^{-T/\tau}\,\Delta\delta E_K + A(1 - e^{-T/\tau})\,\Delta\delta S_K \qquad (3\text{-}4)$$

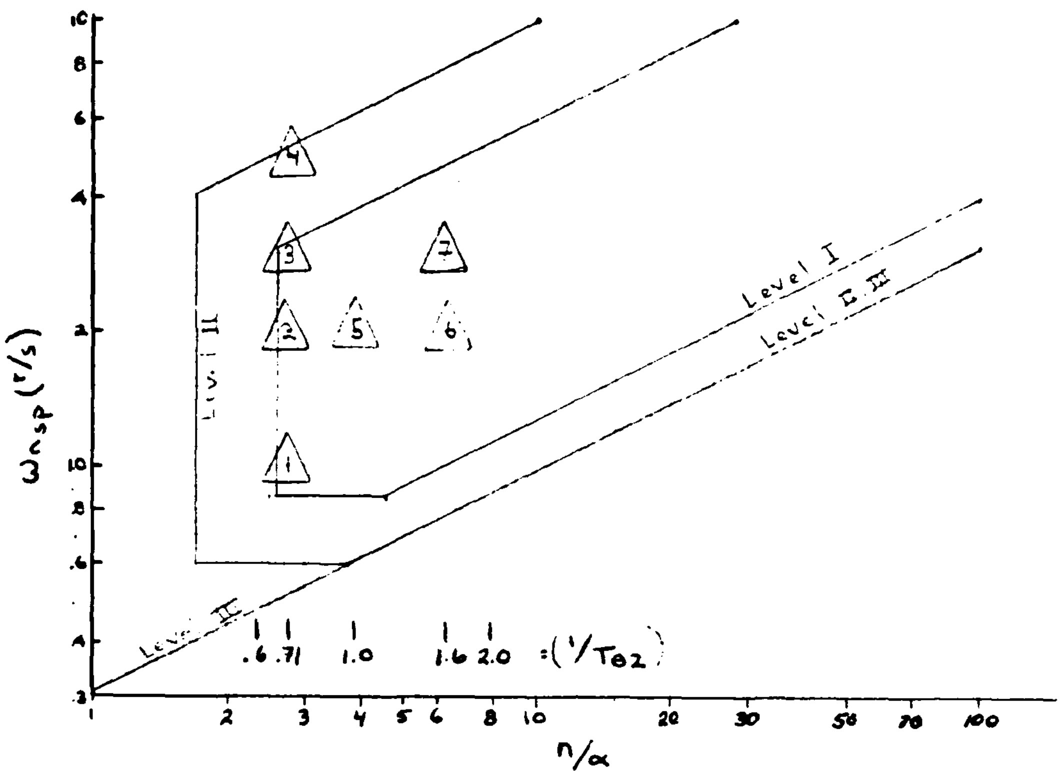

Figure 3.1 Base Configurations

This is implemented in the flight control program as shown in Fig. 3.2.

Values of the prefilter time constant were computed so that the numerator time constants of the L_α-free equivalents equal 1.6, in order to compare these configurations more directly against the base configurations. The prefilter values thus calculated are:

Config.	$1/T_{pf}$
01	7.5
02	3.65
04	1.2

The prefilter configurations are shown in Fig. 3.3 and are listed in Table 3.2.

TABLE 3.2

Flight Test Configurations

CONFIG	$1/T_{\theta_2}$ (1/sec)	FREQ (r/sec)	ZETA	$1/T_{PF}$ (1/sec)	T_D* (sec)	COMMENT	MISMATCH
01	.71	1.0	.7	-	0.064	BASE	-
02	.71	2.0	.7	-	0.064	"	-
03	.71	3.0	.7	-	0.064	"	-
04	.71	5.0	.7	-	0.064	"	-
05	1.0	2.0	.7	-	0.064	"	-
06	1.6	2.0	.7	-	0.064	"	-
07	1.6	3.0	.7	-	0.064	"	-
11	.71	1.0	.7	7.5	0.064	01 + 1/Tpf	-
12	.71	2.0	.7	3.65	0.064	02 + 1/Tpf	-
13	.71	5.0	.7	1.2	0.064	04 + 1/Tpf	-
22	.71	2.0	1.0	-	0.164	Eq. of 13	23
23	1.6	1.25	.7	-	0.164	Eq. of 11	21
25	.71	1.5	.55	-	0.164	Eq. of 12	45
26	1.6	2.0	.4	-	0.164	Eq. of 12	23
27	.71	1.0	.7	-	0.164	Eq. of 11	31
28	1.6	3.0	.7	-	0.164	Eq. of 13	16
31	.71	1.0	.7	-	0.164	01 + Delay	-
32	.71	1.0	.7	-	0.214	01 + Delay	-
33	.71	1.0	.7	-	0.264	01 + Delay	-
34	1.6	3.0	.7	-	0.164	07 + Delay	-
35	1.6	3.0	.7	-	0.214	07 + Delay	-
36	1.6	3.0	.7	-	0.264	07 + Delay	-

* τ_D = Computation Delay (.009) + Sampling Lag (.025) + Servo Lag (.030) + Added Delay (Variable), sec

For each prefilter configuration, two equivalent configurations were calculated. The equivalent systems computations were performed using the program NAVFIT [4]. The program was made available by the Naval Air Development Center, of Warminster, PA, as program EQ3BM. Of the two equivalent configurations, one was

TABLE 3.3

Transfer Functions

Base: $$\frac{\Delta q(s)}{\Delta\delta S(s)} = \frac{A\ (1/T_{\theta 2})}{[.7, 48]\ [\zeta_{sp}, \omega_{sp}]}$$

Prefilter: $$\frac{\Delta q(s)}{\Delta\delta S(s)} = \frac{A/T_{pf}\ (1/T_{\theta 2})}{(1/T_{pf})\ [.7, 48]\ [\zeta_{sp}, \omega_{sp}]}$$

Equivalent: $$\frac{\Delta q(s)}{\Delta\delta S(s)} = \frac{A\ (1/T_{\theta e})\ e^{-\tau_d s}}{[\zeta_e, \omega_e]}$$

Time delay: $$\frac{\Delta q(s)}{\Delta\delta S(s)} = \frac{A\ (1/T_{\theta 2})\ e^{-\tau_d s}}{[\zeta_{sp}, \omega_{sp}]}$$

Notation: $[\zeta, \omega]$ represents $s^2 + 2\zeta\omega s + \omega^2$
(σ) represents $s + \sigma$

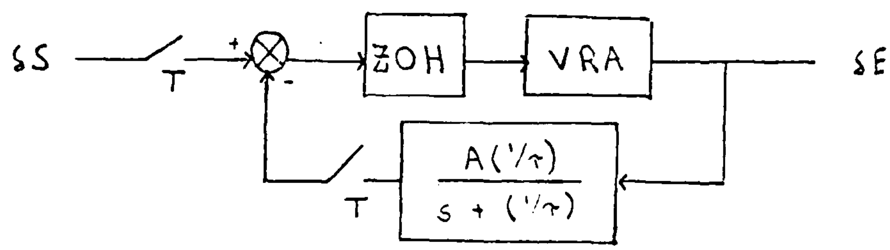

Figure 3.2. Digital Prefilter Implementation.

calculated with L_α fixed during the match, and the other, with L_α free to vary, in order to improve the mismatch. The resulting equivalent configurations are shown in Fig. 3.4 and are listed in Table 3.2.

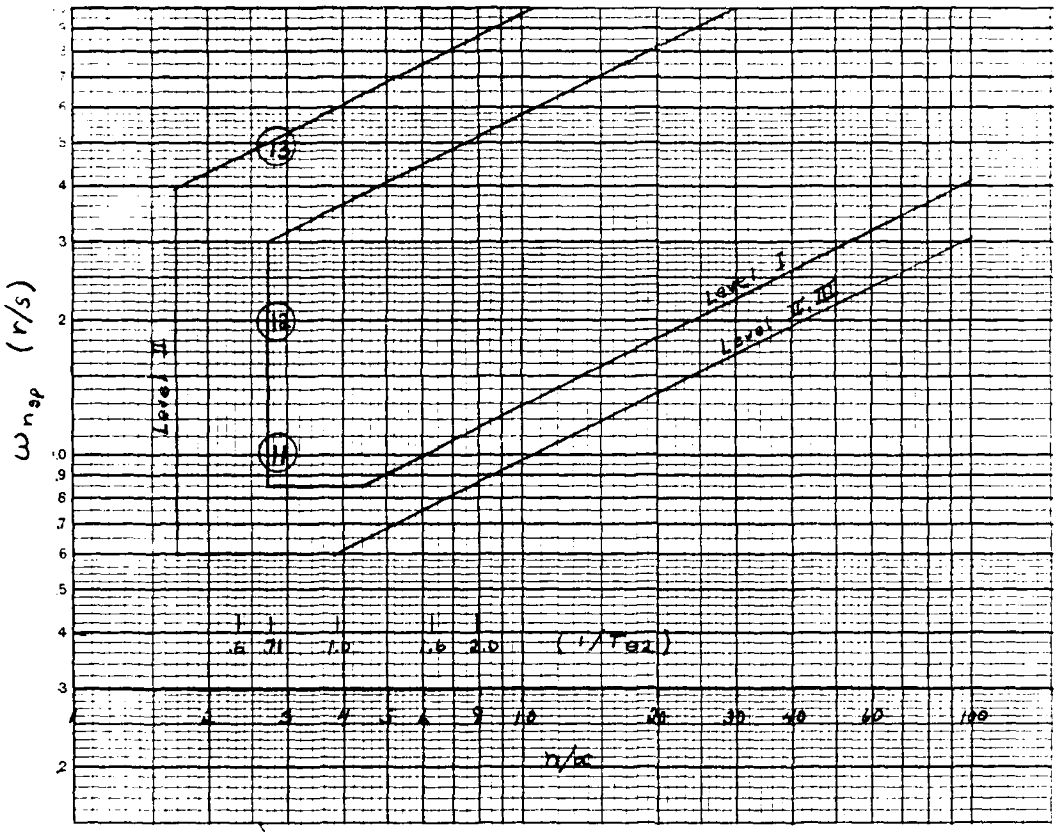

Figure 3.3. Prefilter Configurations.

The time delays, including those in the time delay configurations and those in the equivalent configurations, were implemented with a ring buffer in the Micro-DFCS control program. After the control surface deflection was calculated in the program, it was stored for the appropriate number of sample intervals, and then output. This is shown in Fig. 3.5.

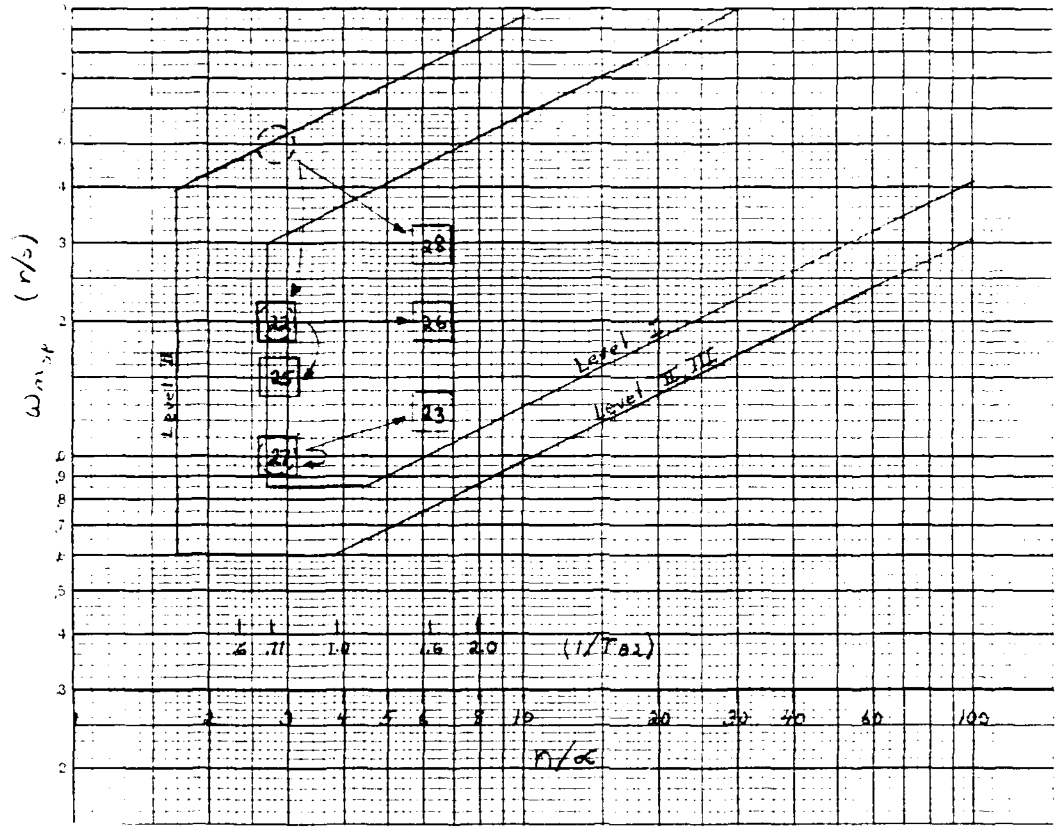

Figure 3.4. Equivalents of Prefilter Configurations.

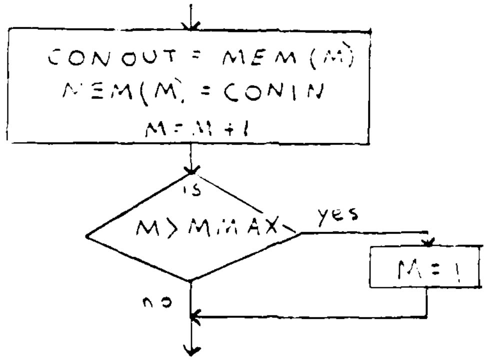

Figure 3.5. Time Delay Implementation.

3.1.2 Approach Task

As the flight test configurations were selected to simulate Class IV aircraft, the task was selected to simulate Category C flight conditions. The task was meant to provide visual and motion cues to the pilot that simulate a carrier approach and landing. To this end, a Navy Field Carrier Landing Practice (FCLP) approach mirror was set up at the approach end of the active runway of Princeton's Forrestal Airfield. The mirror was used to set up a 2.8 deg glide slope. The approach was flown at a speed of 75 kt, first using miror guidance, followed by touchdown. The glide slope was equivalent to a 3.5 deg slope on an aircraft carrier with a 20-kt wind-over-the-deck. The resulting maximum rate of descent was 50 percent of the structural limit of the VRA.

3.1.3 Pilot Comment Cards

Pilots were asked to rate the test configurations on a standard Cooper-Harper Pilot Opinion Rating scale, as described in Chapter 2. There has been some discussion previously regarding the approach task ratings. The discussion centers on the necessity or appropriateness of the pilot including the flare and touchdown portion of the landing in his subjective evaluation of the aircraft. In a Navy carrier landing, the flare is not used at all. The aircraft hits the deck with a sink rate determined by the final glide slope; thus, it is reasonable to limit the rating to the approach. In conventional runway landings, the flare and touchdown may be a more demanding task than the approach. Severe PIOs, which were not evidenced during the approach, have occurred during the flare [9]. Thus, it appears desirable to rate the flare and landing as well. For the current study, separate ratings were asked of the pilots for the approach task, using the FCLP "meatball"*, and for the flare and touchdown. The pilots were asked to comment on the initial response, predictability, PIO tendency, and special techniques used for the pitch attitude response; on initial response, predictability, FCLP tracking, and flare for the flight path response; and on airspeed control. They were asked to comment on and rate performance in general during the approach and on the flare and landing, and they were asked to assess whether the control feel, turbulence, or lateral-directional characteristics were a factor.

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* i.e., the reflected light image whose vertical position relative to a datum bar of lights indicates whether the aircraft is above or below the desired glide slope.

3.2 EQUIPMENT CONFIGURATION OF THE FLIGHT CONTROL SYSTEM

The Variable-Response Research Aircraft (VRA) used in the flight tests is a highly modified Navion. The VRA and its capabilities are described in Appendix A. The flight control system of the VRA consists of analog and digital systems, each of which has the capability for closed-loop control. Inputs to both analog and digital systems are from experimental cockpit controls located at the right pilot station and from air-data and inertial sensors. The analog flight control system consists of amplifiers and a set of feedback and feedforward potentiometers, which can be adjusted in order to alter the effective stability and control derivatives. There are filters on the outputs of the analog system which provide some high-frequency filtering. The digital flight control system uses a Zilog Z80 central processing unit and an AM 9511 arithmetic processing unit; it is described in Appendix A. The Micro-DFCS can execute a complex flight control program at a constant sampling interval of 50 milliseconds or less.

For this project, the analog system provides closed-loop stability augmentation, and the digital system provides open-loop control from the pilot to the analog/airframe system. Inputs from the longitudinal stick and the throttle are fed into the digital system to mechanize the prefilter and delay on the stick and to allow a proportional gain on the throttle. Inputs from the air-data and inertial sensors, plus the lateral-directional controls, are sent to the analog system. The analog system alters the longitudinal characteristics by the dynamic response matching technique, and retains the basic VRA lateral-directional dynamics.

3.3 SOFTWARE

3.3.1 Development System

The digital software development was accomplished on the FRL ground station microcomputer system described in Appendix A. Briefly, it consists of the MSC 8009 SBC, which contains a Zilog Z80 processor, an AM 9511 math processor, and 32K of on-board memory; additional circuit boards which contain more memory; two floppy-disk drives; a console CRT and keyboard; and a line printer. The system software includes the CP/M operating system, a text editor, Pascal complier, a "debugger", and a utility program which generates hex-code files from binary files. The system can interface with an EAI TR-48 analog computer, the aircraft digital microcomputer, and Offner 6-channel thermal chart recorder, and with various oscilloscopes and function generators. This system provides the Flight Research Laboratory with the self-contained capability to create, edit, compile, and test programs written in high-level languages.

3.3.2 pCAS

The digital flight control program is called pCAS, which stands for Pascal Command Augmentation System. The Pascal/MT compiler implements the control logic, and it provides redirected input/output, interrupt procedures, and logical bit manipulation. pCAS was modified from an existing program to implement the control functions explained in Section 3.1.1 while minimizing the execution time of the control routine. All operations that can be accomplished outside of the control routine are done in the setup routine. This includes pre- and post-multiplication of the gain matrices by the conversion factors of the input sensors and output servos. Thus, the control procedure executes the minimum number of operations.

The pCAS control modes were numbered from 1 through 6. Mode 1 was the prefilter used in Configuration 11, Mode 2 was the Configuration 12 prefilter, and Mode 3 was the Configuration 13 prefilter. Mode 4 was the time delay for Configurations 22 through 28, 31, and 34; Mode 5 was the time delay for 32 and 35; Mode 6 implemented Configurations 33 and 36.

In addition to providing control functions, pCAS has utility routines for changing the sampling rate, testing the A/D and D/A channels, adding step inputs, setting delays manually, and altering the gains of the input and output channels. All of these utility routines operate "in the background", that is, when the control routine is not operating. Thus, it is necessary to have some "spare time" between the end of the control routine and the next interrupt to perform these routines.

3.3.3 Testing and Validation

In order to test the flight control program, a hybrid simulation was done with the Micro-DFCS connected to the EAI TR-48 analog computer. The analog computer was programmed to simulate the fourth-order, linearized longitudinal dynamics of the 7 base configurations. The program generated $\Delta\theta$, Δq, Δn_z, $\Delta\alpha$, and ΔV from $\Delta\delta E$, which was generated by the micro-DFCS. The pitch stick input, $\Delta\delta S$, was generated by a joystick from a model aircraft radio control system, whose gain was scaled by the analog computer before being sent to the microcomputer. The analog computer diagram and potentiometer settings are shown in Appendix A.

During the simulation runs, step inputs were given to the joystick, and the response of the system was recorded on a six-channel thermal chart recorder. The traces were analyzed to determine that the delay times and prefilter rise times were correct. Also, the traces were used to analyse the configurations in terms of the proposed criteria.

In addition, pCAS was analyzed with an oscilloscope to determine the execution time and duty cycle of the control routine. The routine executed in 37 milliseconds, for a duty cycle of 74 percent. This duty cycle left sufficient time for execution of the utility routines.

Chapter IV
FLIGHT TESTING AND RESULTS

Flight testing consisted of approximately three flights with each of five evaluation pilots. Each pilot evaluated all 22 configurations. The first pilot to evaluate any configuration was Princeton's chief test pilot. The other pilots involved in flight testing were Navy test pilots from the U.S. Naval Air Test Center, Patuxent River, MD. As much as possible, flights were conducted in the early morning, when the air normally was calm. The first flights in the program were used to match the dynamic response of each of the analog configurations. In addition, on these flights the digital program was tested to insure its proper operation in the aircraft environment.

4.1 PROCEDURES

After the matching flights were completed, the test flights began with Princeton's test pilot as the evaluation pilot. During each flight, the aircraft was manned by a crew of two: the safety pilot, who occupied the left seat, and the evaluation pilot, who sat in the right seat. Procedures used during the flight tests were as follows. The FCLP mirror was set up at the south end of Runway 2/20, which is a 3000 ft, tarmac runway located on the Forrestal Campus of Princeton University. After the mirror was set up, the aircraft was started, and, as the pilots completed the pretakeoff check, the pCAS program was loaded, through an RS-232 cable, from the FRL ground station into the aircraft's Micro-DFCS. After take-off, the analog system was set up for the first configuration by the safety pilot. The safety pilot also set the digital system with the proper mode and time delay. Once the aircraft was in a trimmed condition at 75 kt on the downwind leg of the approach, the flight control systems were engaged and the evaluation pilot took control of the aircraft. The safety pilot radioed to the ground station at this point.

On the ground, the telemetry data were being received by an FM receiver. The data were recorded during approaches on a Honeywell 7600 tape recorder. The data also were routed to the FRL ground station digital Telemetry Monitoring system, which selected six of the forty-two TM channels of data for "quick look" display and sent this data through the analog computer (for scaling and biasing) to the strip chart recorder. The six channels included stick position, pitch attitude and rate, normal acceleration, angle of attack, and velocity. The ground station operator would turn on the tape recorder and the strip chart recorder when the aircraft began an approach. The safety pilot would radio again when the aircraft was on final approach and had acquired the FCLP "meatball". The evaluation pilot would attempt to maintain the approach speed of 75 kt and keep the meatball centered in the mirror. The pilot would attempt to flare the aircraft and touch down. If at any time the safety pilot had any doubt about the safety of the approach, he could disengage the flight control systems and regain manual control of the aircraft, or he could engage the abort mode of the aircraft, which automatically applies climb power to the engine and moves the flaps to 20° downward deflection. Once the aircraft had touched down and begun a go-around, or if the landing had been aborted, the ground station operator would switch off the tape recorder and the strip chart recorder. On the go-around, the safety pilot would re-adjust the analog system for the next configuration while the evaluation pilot wrote his comments on the evaluation form.

4.2 ANALYSIS OF RESULTS

The twenty two configurations were subjectively rated by five test pilots identified as A,B,C,D, and E. Pilot B evaluated and rated the final approach (app) handling characteristics for each flight. Pilots A,C, and D not only evaluated the approach but separately evaluated the critical close region immediately prior to impact (cls) as well. Pilot E did not fly the approach and land task, but he based his evaluation only on pitch response to stick input at altitude.

Flight test ratings and pilot comments are included in

Appendix C of this report. Each Handling Qualities Rating (HQR) signifies the average rating of at least two consecutive approaches. Multiple ratings indicate that another two consecutive approaches were flown again later in the program. Generally, the multiple ratings indicated consistent pilot evaluation. Of the 91 repeat ratings, only 8 ratings differed by more than one standard deviation from the individual pilot's average rating for that configuration. Three of these eight ratings were significantly greater than two standard deviations of the overall rating average for that configuration and were considered outliers. These include: Pilot B, config. 06 (app), HQR - 7; Pilot B, config. 23 (app), HQR - 8; Pilot C, config. 06 (cls), HQR - 7. Excluding these outliers, the multiple ratings were averaged for each pilot,and these average ratings are presented in Tables 4.1 and 4.2. The deviation of all ratings and all pilots for each configuration has the following mean and standard deviation: (app) mean = 1.05, sigma = 0.45; and (cls) mean = 1.00, sigma = 0.51. This is consistent with rating scatter in other Handling Qualities experiments.

CAP_1 and CAP_2, were calculated for each configuration using the equations shown below. Values were calculated by using a second-order computer simulation to determine the time necessary for the pitch rate response to first reach its steady state value ($\Delta t^*_{q_1}$). For the CAP_2 values, $\Delta t^*_{q_2}$ included the

Table 4.1

Approach (Average) Ratings

	A	B	C	D	E	mean	s.d.
01	3.5	3.0	2.0	3.3	5.0	3.36	1.08
02	4.3	3.0	3.0	4.0	2.0	3.26	.92
03	3.3	3.0	2.0	2.3	3.5	2.82	.65
04	5.0	5.0	2.0	3.5	3.0	3.70	1.30
05	4.0	4.0	3.0	3.0	3.5	3.50	.50
06	3.5	3.0*	3.0	4.0	3.0	3.30	.45
07	3.4	3.0	2.1	2.3	2.0	2.56	.61
11	4.5	5.5	4.5	4.0	4.6	4.82	.70
12	4.3	3.0	3.5	4.0	5.0	3.96	.76
13	6.0	6.0	2.0	4.0	3.0	4.20	1.79
22	6.5	7.0	3.0	5.0	3.0	4.90	1.88
23	3.5	3.0*	3.0	4.0	5.0	3.70	.84
25	4.8	4.0	3.5	4.0	4.5	4.16	.50
26	4.0	7.0	4.0	4.3	6.0	5.06	1.37
27	4.5	3.0	2.7	3.0	5.8	3.80	1.32
28	3.0	6.3	3.0	3.0	2.5	3.56	1.55
31	4.5	4.0	3.0	5.0	5.0	4.36	.86
32	5.3	4.0	2.5	5.7	7.0	4.90	1.72
33	6.0	6.0	3.5	6.0	8.0	5.90	1.60
34	3.0	5.0	2.0	3.0	4.0	3.40	1.14
35	3.8	4.0	2.0	3.0	3.0	3.16	.79
36	4.0	4.0	2.3	4.0	3.0	3.46	.78

*outlier excluded

Table 4.2

Close (Average) Ratings

	A	C	D	mean	s.d.
01	4.0	3.3	4.0	3.77	.40
02	5.3	4.0	4.5	4.60	.66
03	3.8	2.5	3.3	3.20	.66
04	5.0	3.0	4.0	4.00	1.00
05	4.0	3.0	3.0	3.33	.58
06	3.0	2.0*	4.0	3.00	1.00
07	3.1	2.0	3.3	3.10	.20
11	4.3	6.5	7.0	5.93	1.44
12	5.3	5.0	5.0	5.10	.17
13	7.0	3.0	5.0	5.00	2.00
22	7.0	4.0	7.0	6.00	1.73
23	4.8	4.0	6.0	4.93	1.01
25	4.8	5.5	6.0	5.43	.60
26	4.0	6.0	7.0	5.67	1.53
27	4.5	4.2	6.0	4.90	.96
28	3.3	4.0	5.0	4.10	.85
31	4.8	4.5	7.0	5.43	1.37
32	6.0	4.5	6.0	5.50	.87
33	7.0	5.5	7.0	6.50	.87
34	4.0	3.0	5.0	4.00	1.00
35	4.3	3.0	7.0	4.77	2.04
36	4.3	4.0	6.0	4.77	1.08

*outlier excluded

appropriate time delay. Values were determined by the following expressions:

$$CAP_1 = \frac{\Delta q^*}{\Delta n^*_{z_\alpha} \; t^*_{q_1}} \tag{4-1}$$

$$CAP_2 = \frac{\Delta q^*}{\Delta n^*_{z_\alpha} \; t^*_{q_2}} \tag{4-2}$$

Table 4.3

CAP_1 and CAF_2 Values

Config	CAP_1	CAP_2	Config	CAP_1	CAP_2
			22	1.38	.86
			23	.20	.19
01	.36	.32	25	.97	.68
02	1.43	1.31	26	.85	.62
03	3.22	2.50	27	.34	.29
04	8.95	4.19	28	1.49	.90
05	1.02	.91			
06	.64	.53	31	.36	.29
07	1.43	1.19	32	.36	.28
			33	.36	.27
11	.30	.28	34	1.43	.90
12	.76	.67	35	1.43	.80
13	1.34	1.10	36	1.43	.73

From this data base, the following observations concerning CAP_1, equivalent systems, and CAP_2 can be made.

4.2.1 Short Period Natural Frequency Variation

Figures 4.1 and 4.2 show plots of HQR vs. short period natural frequency for constant values of pitch-rate transfer function zero, 0.71 r/s and 1.6 r/s, respectively. These are plotted for each pilot and an average of all five pilots. CAP boundaries dictate marginal Level I ratings degrading to Level II ratings at 4-5 r/s for $1/T_{\theta_2} = 0.71$ r/s, and common Level I ratings for $1/T_{\theta_2} = 1.6$ r/s. Pilot's A,B,C, and D indicated the appropriate degraded rating at high frequency as expected. They also generally agree on a trend of degraded ratings at a natural frequency of 2 r/s. Pilot comments stated that configurations flown with that short period natural frequency were comparatively more sluggish. Pilot E, evaluating pitch response solely, detected no similar trends and found a natural frequency of 2 r/s the most favorable in one case. Observations indicate that for smaller $1/T_{\theta_2}$ values, the "close" ratings tend to be one rating greater than the "approach" ratings. Conclusions drawn are that the present CAP Level II boundary effectively denotes Level II performance at the higher frequency for the landing task but does not explain degraded performance at 2 r/s. Also, CAP apparently does not clearly indicate performance for a pitch response task at altitude.

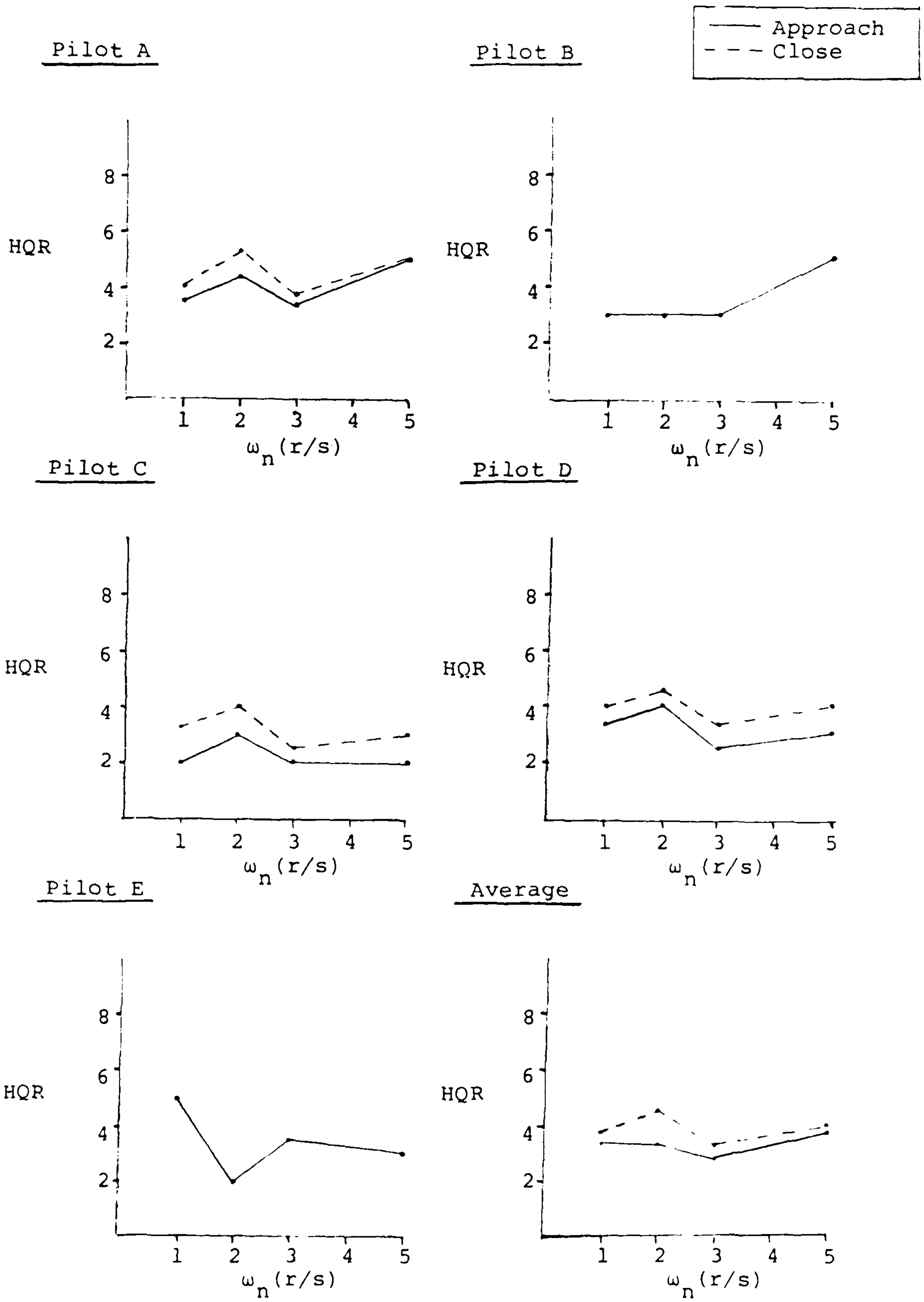

Figure 4.1 $\omega_{n_{sp}}$ Variation ($1/T_{\theta_2}$ = 0.71 r/s).

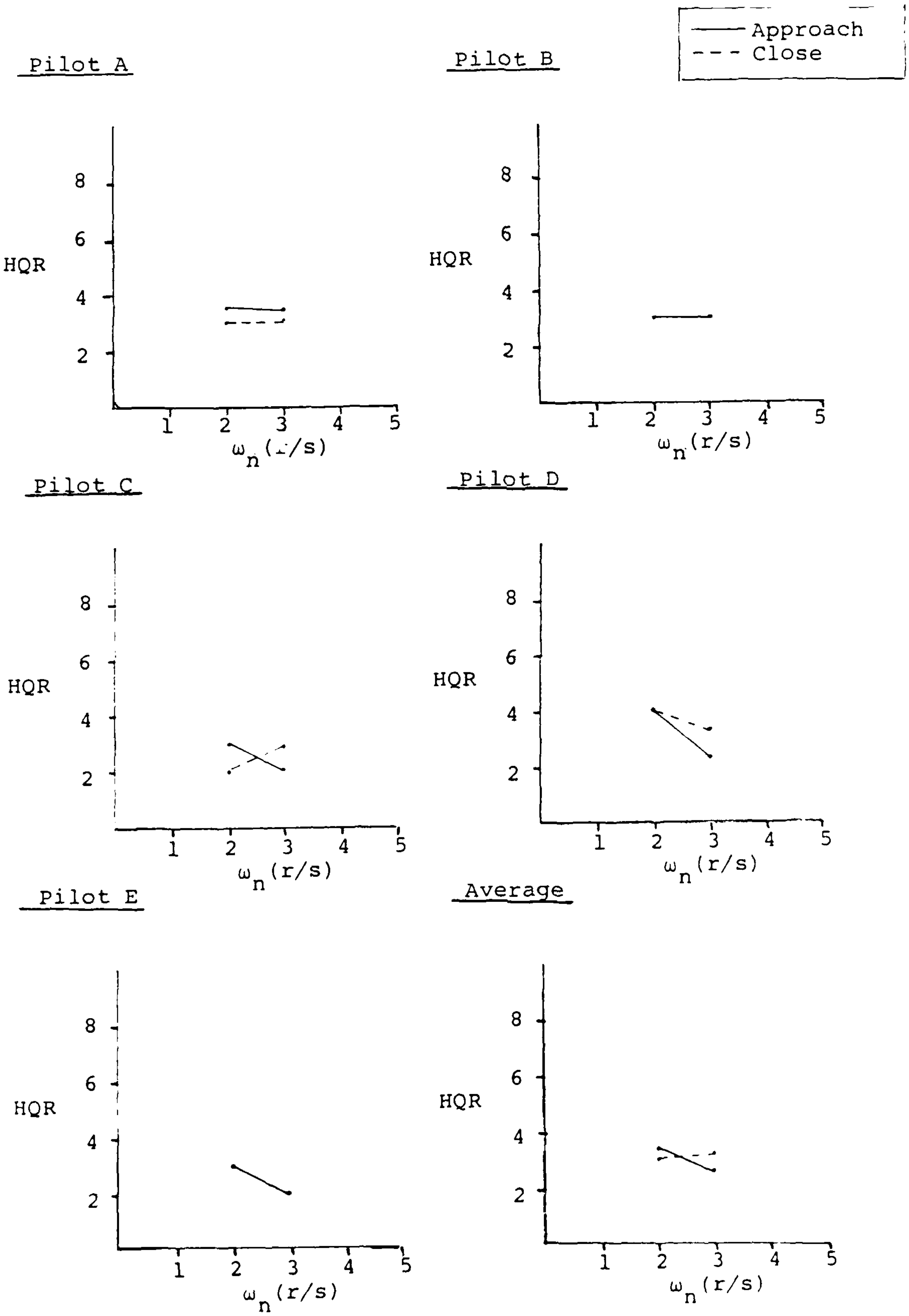

Figure 4.2 $\omega_{n_{sp}}$ Variation ($1/T_{\theta_2}$ = 1.6 r/s).

4.2.2 <u>Pitch-Rate Transfer Function Zero Variation</u>

Present CAP boundaries dictate that Level I performance degrades to "marginal Level I" as $1/T_{\theta_2}$ decreases for a constant short period natural frequency of 2 r/s. Figure 4.3 plots HQR vs. $1/T_{\theta_2}$ for each pilot, as well as an average for all the pilots. Within one rating, pilot's A,B,C, and D rated the configurations as marginal Level I with slight performance drop at lower zero values, as expected. Again, it is noted that the "close" rating are one rating greater at the lower zero values. Pilot E rated the lower zero values better, and again, did not indicate the trend dictated by present CAP boundaries. Observations indicate a valid compatibility with CAP boundaries for the landing task but not for the pitch response task.

4.2.3 <u>Time Delay Variation</u>

Time delays were varied for two particular configurations. One configuration (01) modelled a sluggish response, while another configuration (07) modelled a quicker responding aircraft with a steeper lift curve slope. Handling Qualities Ratings were plotted vs. time delay for these configurations in Fig. 4.4 and 4.5. For both configurations, performance degraded one rating for 0.16 seconds of delay. The slower configuration's degraded linearly with time delay while the HQR of the quicker configuration levelled off as time delay increased to 0.26 seconds. Pilots generally agreed that the time delay was much more apparent in the first series and

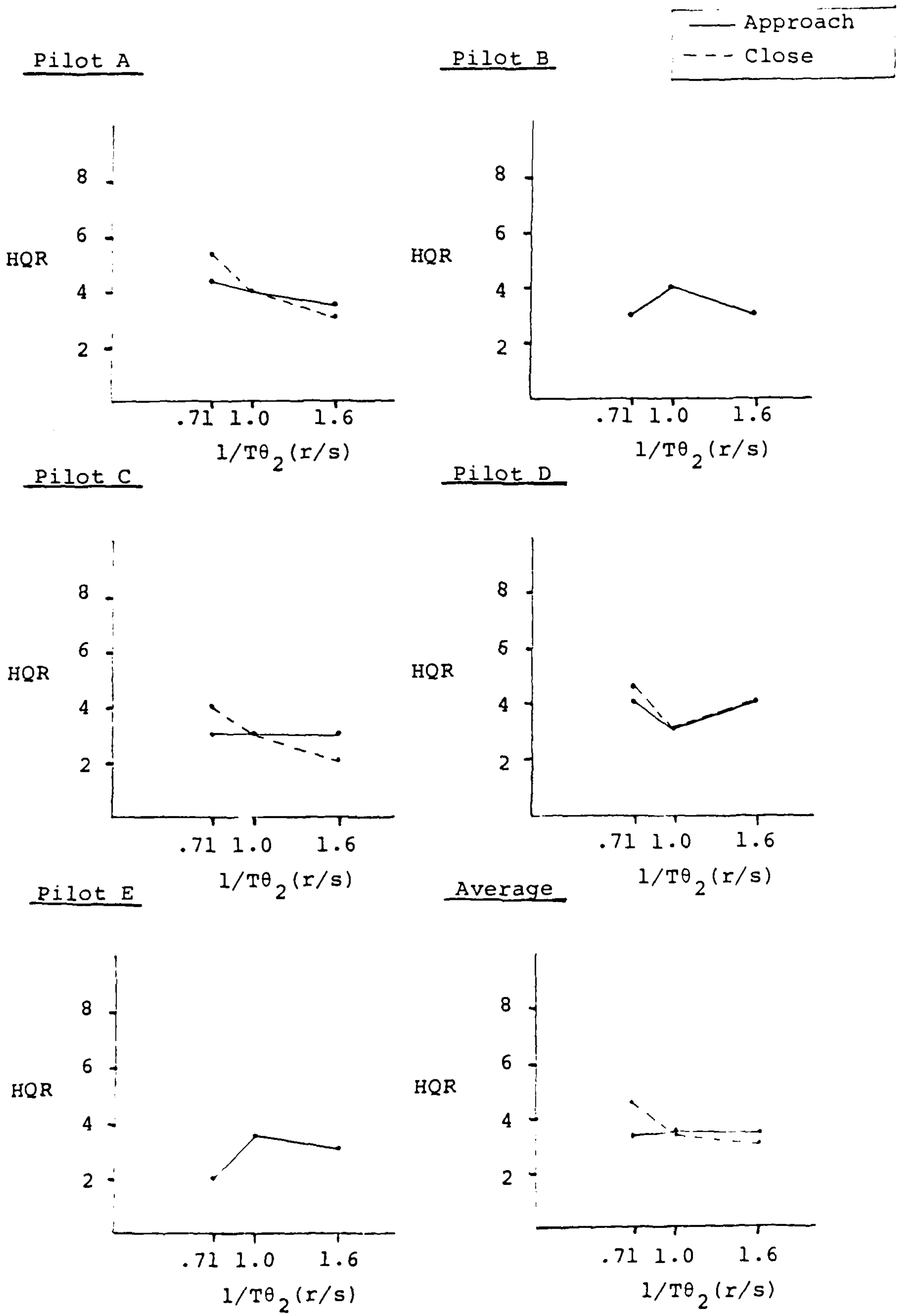

Figure 4.3 Pitch Rate Transfer Function Zero Variation ($\omega_{n_{sp}} = 2$ r/s).

that these delays were usually interpreted as lags in the quicker series. Pilots also noted much more of a PIO tendency in the slower configuration at the higher time delay. These results indicate definite performance drop on the order of one rating by 0.16 seconds of delay and a much more dominant effect as delay increases for slower responding configurations with flatter lift curve slopes.

4.2.4 Equivalent Systems Evaluation

In the equivalent systems evaluation, high-order system (prefilter) ratings were compared to ratings of the low-order equivalent systems (LOES) for both the fixed and free L_α cases. Average and individual handling qualities ratings are plotted in Fig. 4.6 and 4.7. Ratings generally indicate good correlation for both cases. The fixed L_α ratings have less scatter than the free L_α ratings, indicating better equivalency to the higher order systems. There seems to be no apparent bias in the rating comparison. Within pilot repeatability ranges, there was no correlation to cost function, prefilter frequency, or mismatch. Furthermore, equivalence did not seem to be task related. Comparisons were acceptable for the approach task, the close task, and the pitch response task. It is interesting to note that when specifically asked to compare configurations after flight tests,the pilots agreed that corresponding high-order and low-order configurations did not have similar flying characteristics. The time delays were obvious and not

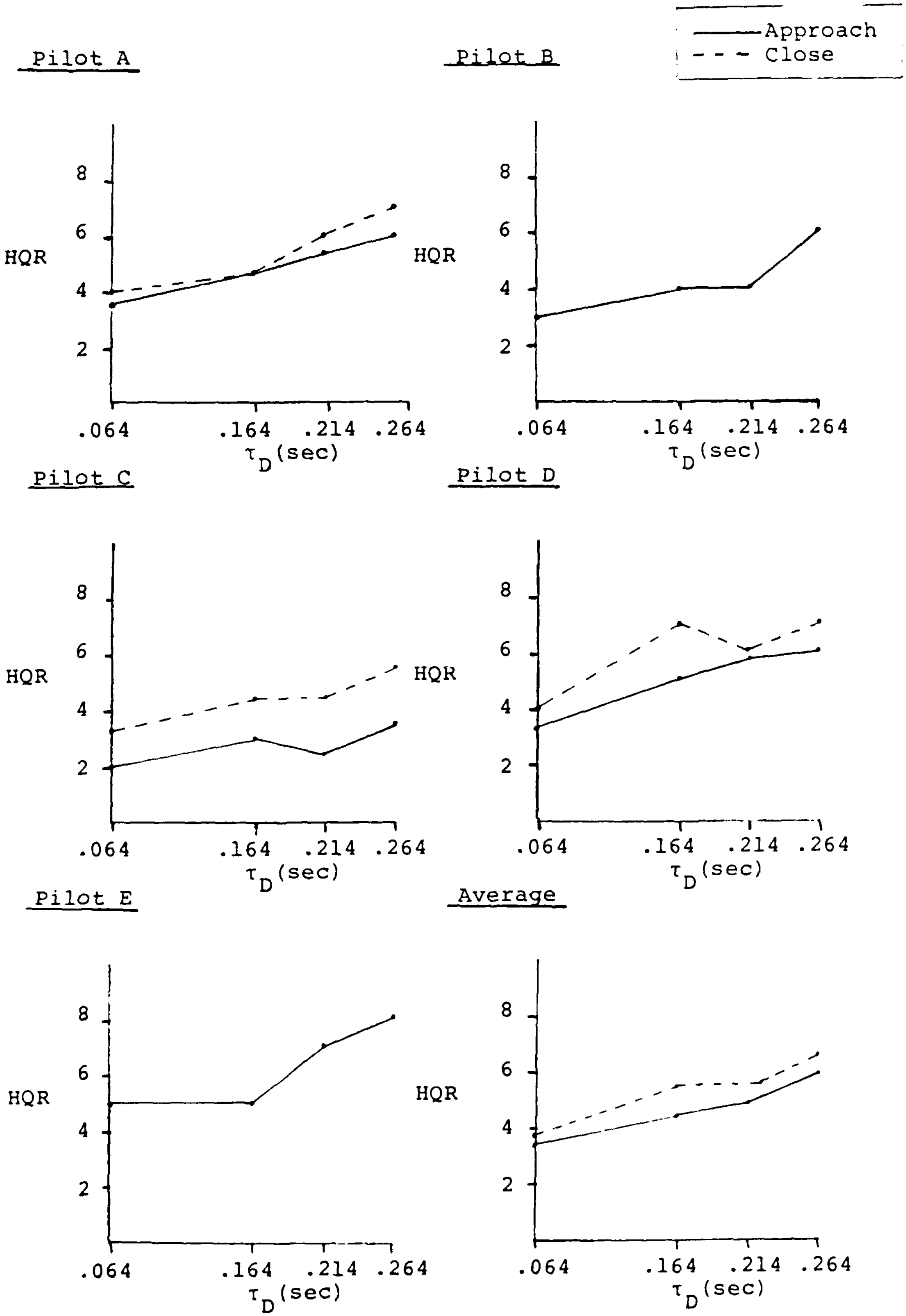

Figure 4.4 Time Delay Variation ($1/T_{\theta_2}$ = 0.71 r/s $\omega_{n_{sp}}$ = 1 r/s).

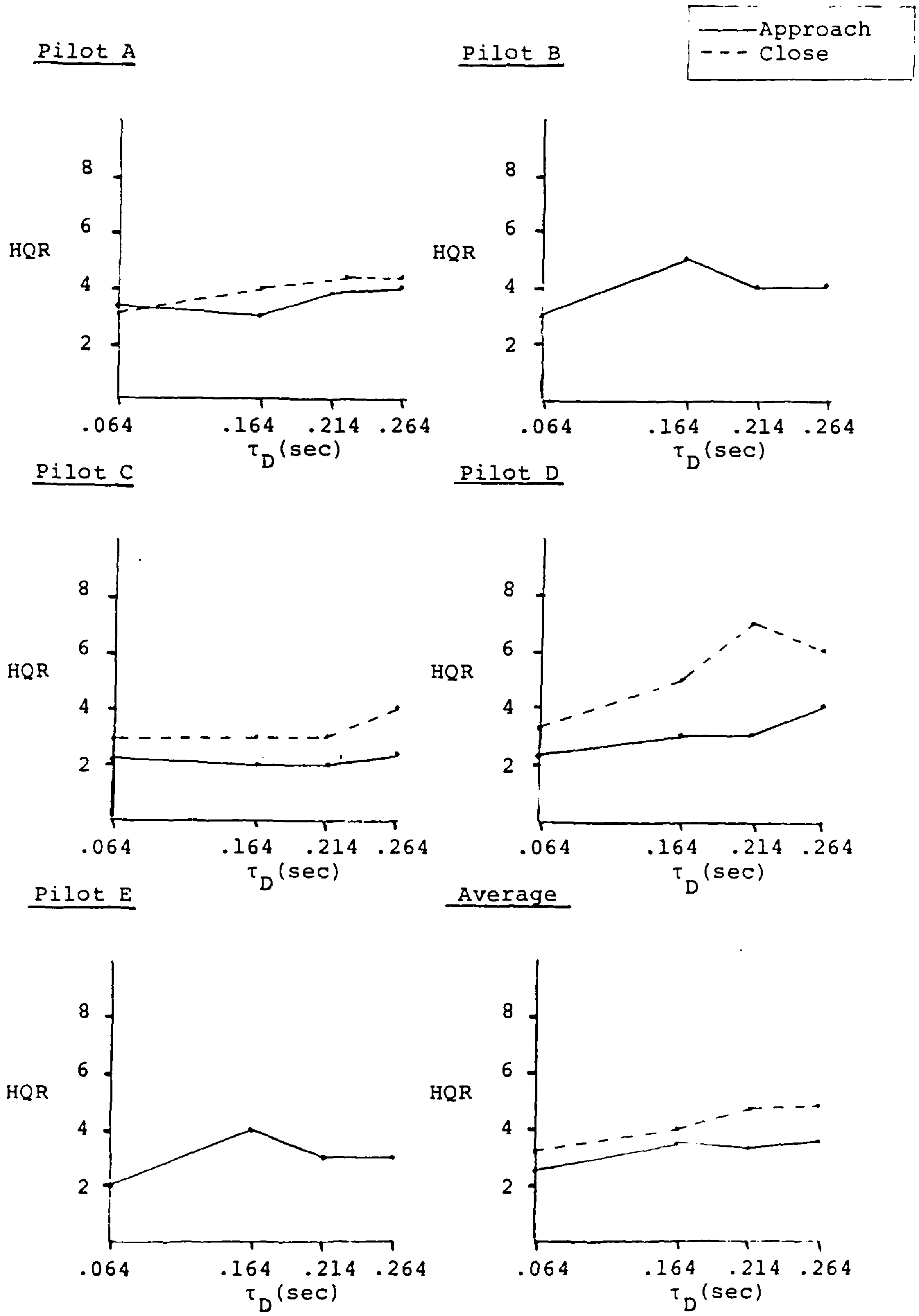

Figure 4.5 Time Delay Variation $(1/T_{\theta_2} = 1.6$ r/s, $\omega_{n_{sp}} = 3$ r/s).

interpreted as the lags they were modelled to represent. Response felt different, but, as the comparisons show, handling characteristics indicated similar performance levels.

4.2.5 CAP_2 Evaluation

Primary configurations 01 - 07 have an inherent time delay of 0.064 sec. As the delay is fixed, CAP_2 values have a one-to-one relationship with CAP_1 values for the configurations and the performance characteristics. Handling Qualities Ratings vs. primary configuration CAP_2 values for each pilot and a pilot average are plotted in Fig. 4.8. As depicted by CAP_2 boundaries, performance degrades to Level II at CAP_2 values approximately less than 0.4 and greater than 3.5. CAP_2 values also do not indicate the degraded ratings for the configurations with a short period natural frequency of 2 r/s.

From this basis, CAP_2 distinguishes itself from CAP_1 in it's ability to incorporate the time delay of a configuration. Using the same two configurations discussed in the TIME DELAY VARIATION section above, HQR were plotted vs. the corresponding CAP_2 values, indicating the effect of time variation on the two primary configurations. CAP_2 values for the delayed configurations should represent the degraded performance by falling into the Level categories determined previously and verified above. Observations clearly show that this was not the case.

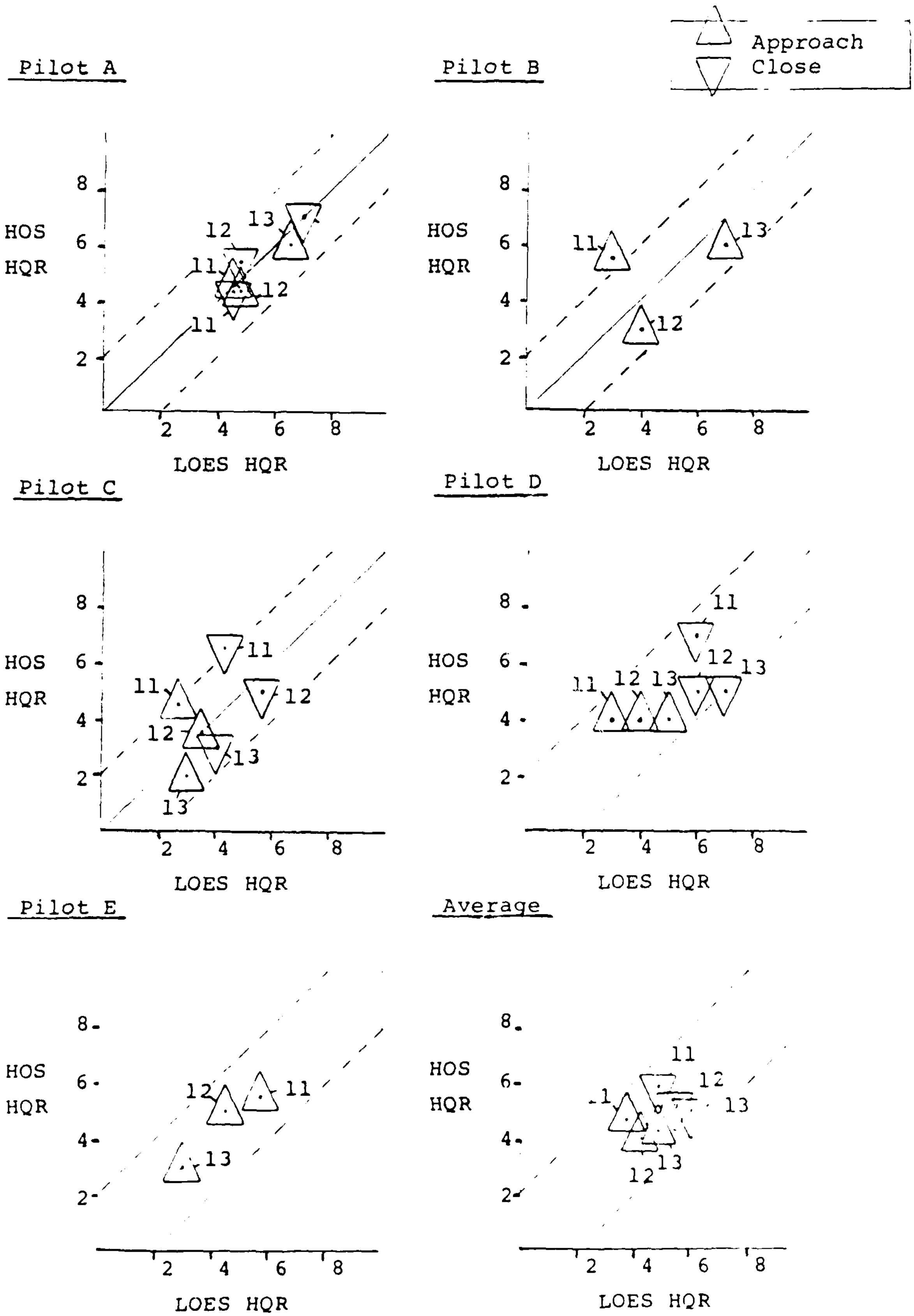

Figure 4.6 Equivalent Systems Evaluation: Fixed L_α.

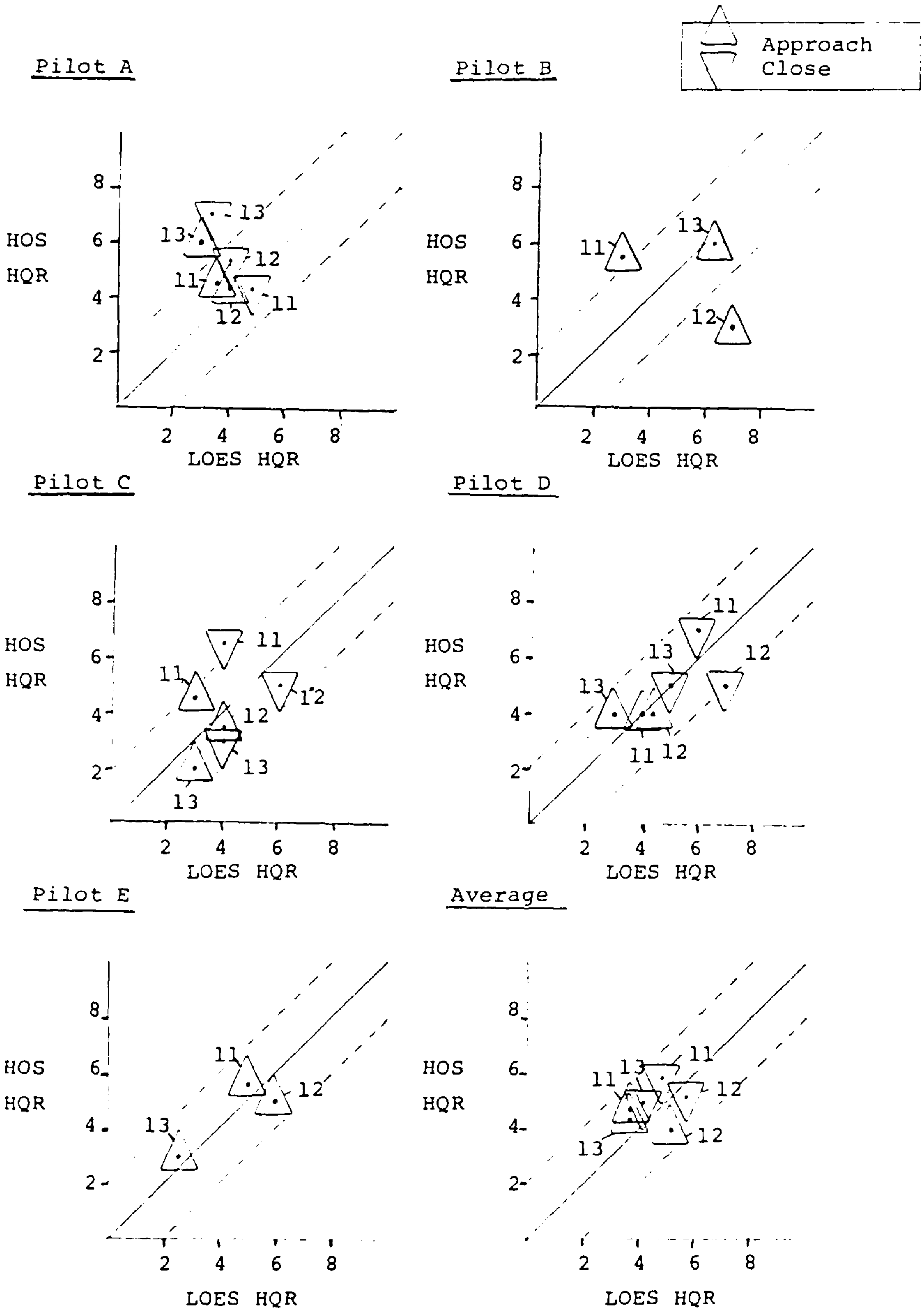

Figure 4.7 Equivalent Systems Evaluation: Free L_α.

In the first case, for the sluggish configuration, performance was already Level II but with delay degraded to Level III before dropping to CAP_2 values less than 0.3. And the CAP_2 values for the quicker configuration, according to the previously determined Level boundaries, should have indicated no change in handling performance. This obviously was not the case. Results demonstrate that CAP_2 values do not effectively evaluate performance drop due to time delay variation.

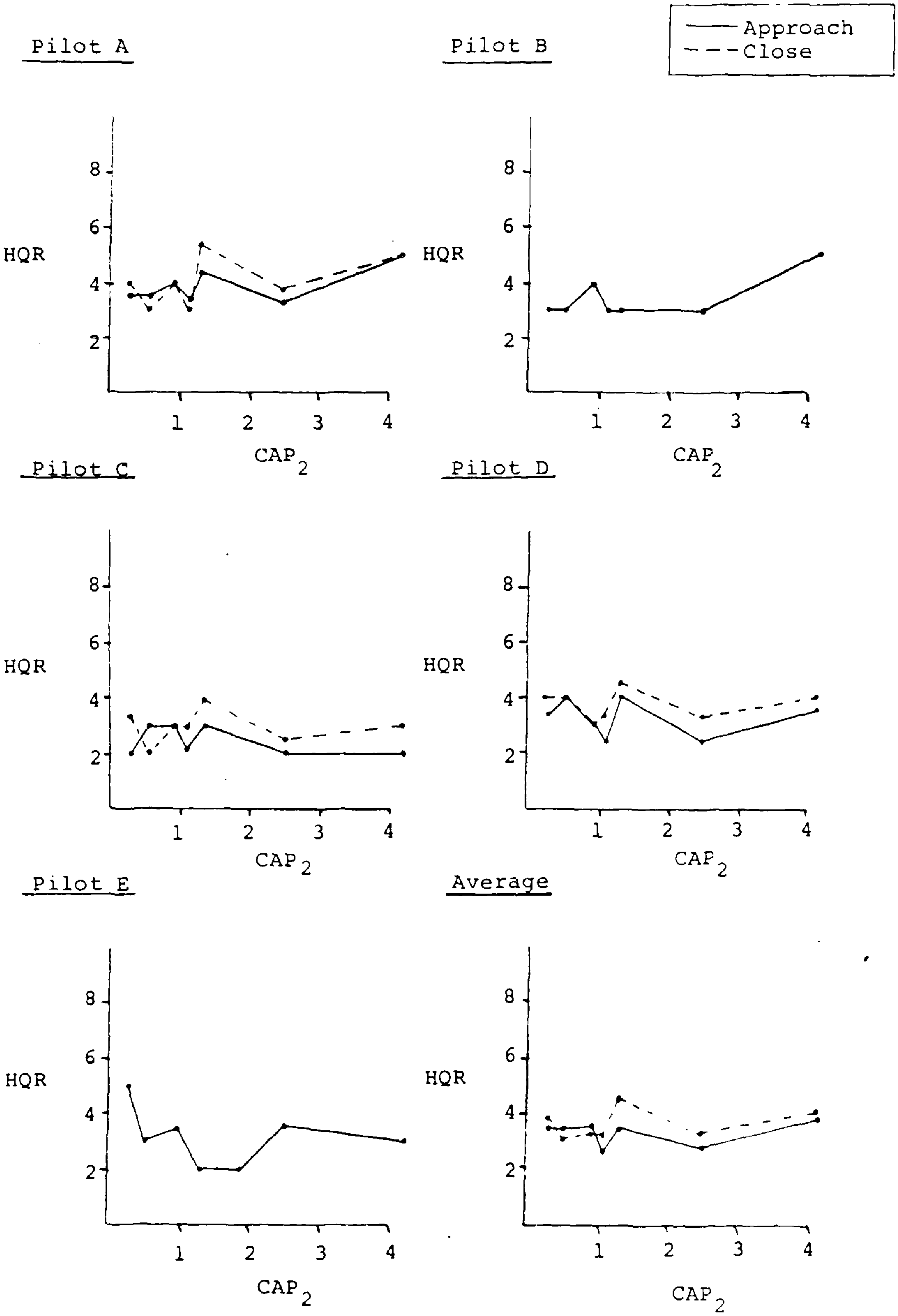

Figure 4.8 CAP_2 Evaluation: (Config 01 - 07) τ_D = 0.064 sec.

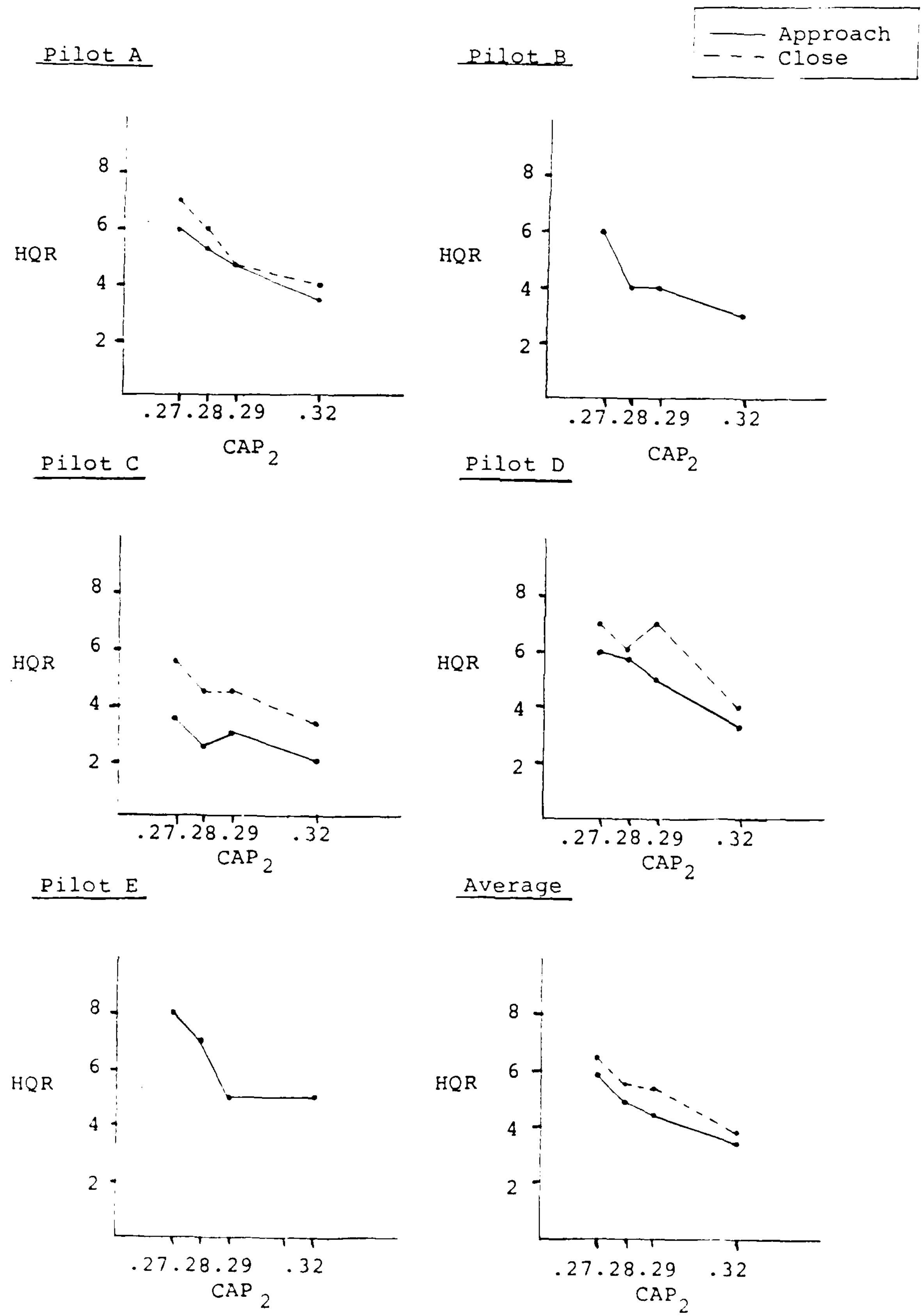

Figure 4.9 CAP_2 Evaluation: τ_D Variation ($1/T_{\theta_2}$ = .71 r/s; $\omega_{n_{sp}}$ = 1 r/s).

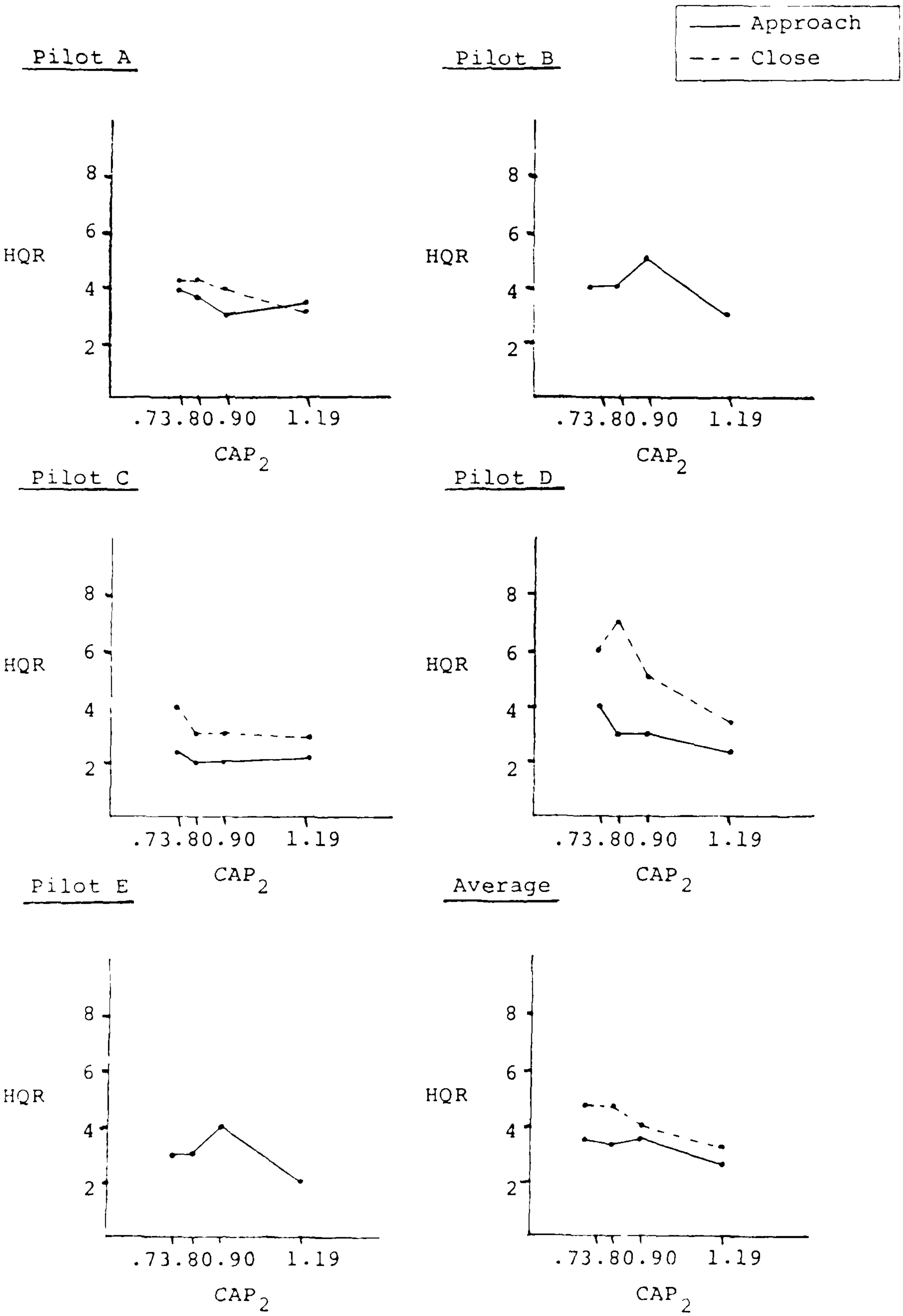

Figure 4.10 CAP_2 Evaluation: τ_D Variation ($1/T_{\theta_2}$ = 1.6 r/s: $\omega_{n_{sp}}$ = 3 r/s).

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

A number of conclusions can be drawn as a consequence of this research relating to longitudinal flying qualities criteria. Flying qualities conclusions are based on a limited number of flights and are of a preliminary nature. All conclusions are summarized below, and additional details can be found in the text.

* Ratings generally indicate a compatibility with present CAP Level boundaries for the primary configurations evaluated, but the CAP boundaries did not explain performance degradation at a short period natural frequency of 2 r/s. Though CAP confirmed landing task ratings, they did not confirm ratings based solely on pitch response.

* "Close" ratings follow "approach" rating trends but tend to be greater for smaller values of $1/T_{\theta_2}$. This condition for a flatter lift curve slope emphasizes the dominant normal acceleration response concerns for the "close" task.

* Time delays of 0.16 seconds consistently degraded handling qualities performance on the order of one rating. Configurations that characterized flatter lift curve slopes and slower short period natural frequencies degraded one Level of performance by 0.26

seconds where pilot induced oscillations on landing were noted. Quicker responding configurations did not degrade performance to this extent for the same time delay variation.

* Though both compared well, fixed L_α configurations more closely correlated with high-order systems than free L_α configurations in the equivalent systems evaluation. Ratings correlated per pilot even though most pilots were evaluating landing tasks and one was evaluating a pitch response task at altitude.

* CAP_2 parameters did verify determined Level boundaries, but, as with CAP_1 they did not explain performance degradation at a short period frequency of 2 r/s. CAP_2 did not successfully evaluate time delay effects.

* The landing task evaluation was significantly different from the pitch response task at altitude.

5.2 RECOMMENDATIONS

Further study should be conducted to evaluate performance characteristics at and around a short period natural frequency of 2 r/s. Rating repeatability could verify or deny actual performance degradation at this frequency.

For the CAP_2 evaluation, the change in initial pitch rate should be reevaluated to better discern the effects of time delay variation. CAP_2 values for configurations with time delay should adhere to the CAP_2 Level boundaries.

This program of flight experimentation was directed at developing and verifying longitudinal flying qualities criteria for high-order flight control systems with time delay effects. Conclusions drawn are hoped to contribute to a better understanding of how to evaluate the new breed of flying machine.

Appendix A

RESEARCH SYSTEMS DESCRIPTIONS

A.1 VARIABLE-RESPONSE RESEARCH AIRCRAFT (VRA)

The VRA is a highly modified Navion equipped with inertial, air data, and navigation sensors, as well as six independent force and moment controls. The VRA, shown in Fig. A.1, has been used to conduct a broad range of experiments in aircraft flying qualities, human factors, and control in the past. The aircraft has played a major role in establishing current military and civil flying qualities criteria, and with the addition of the Micro-DFCS, the VRA is equipped to expand this type of research, as well as to investigate advanced digital control concepts.

Independent control of three forces and three moments is provided by commands to the elevator, ailerons, rudder, throttle, direct-lift flaps, and side-force panels (Figure A.2). The control surfaces are driven by hydraulic servos originally fitted to the B-58 aircraft. The modified VRA units incorporate solenoid-actuated valves with force-override features for quick disengagement. Characteristics of the control effectors are summarized in Table A.1. Surface rate limits are seen to range from 60 to 110 deg/sec. Band-

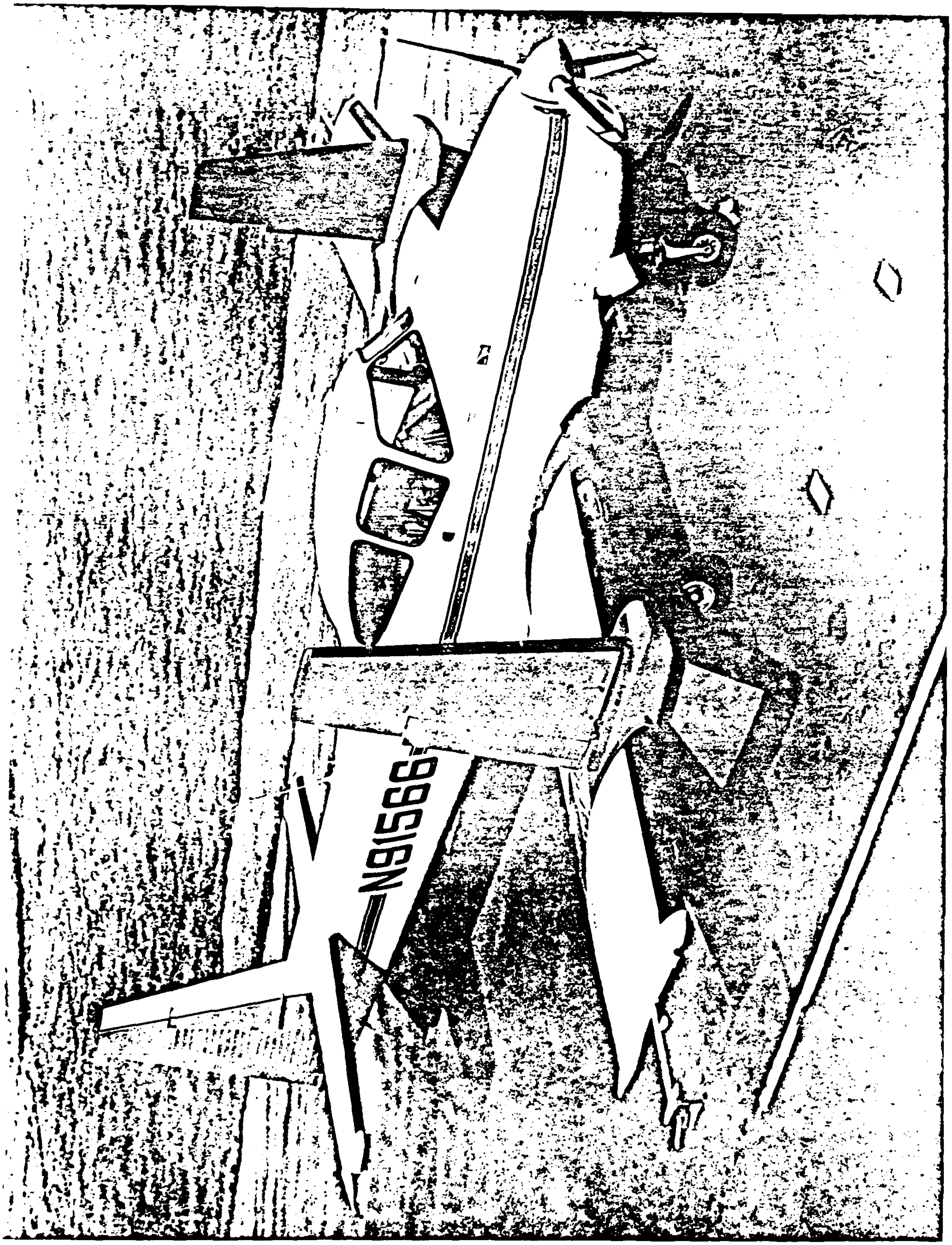

Figure A.1. Variable-Response Research Aircraft.

widths are given for flat response and 6 db attenuation (in parentheses), except that thrust bandwidth is specified by the frequency for 3 db attenuation. The aircraft's normal operating speed range is 65 to 120 kt; maximum specific forces and moments ("control power") are given for 70 kt airspeed. At IAS = 105 kt, maximum direct lift and side-force accelerations are 1 g and 0.5 g, respectively.

The sensors used for most flight testing include angular rate gyros and linear accelerometers for all three axes, vertical and heading gyros, dual angle-of-attack and sideslip-angle vanes, radar altimeter, indicated airspeed, control surface positions, and cockpit control positions. Several other signals (e.g., air temperature, barometric altitude, altitude rate, and TALAR microwave landing system signals) are available for system feedback or telemetry recording. The present telemetry system allows 42 data channels to be multiplexed and transmitted to the FRL ground station described below.

The aircraft is flown by a two-man crew during all research. This provides a number of advantages in comparison to single-pilot operation from the standpoint of flight safety and experimental efficiency. The instrument panel and controls are shown in Fig. A.3. The conventional mechanical aircraft system is flown by the safety pilot in the left seat while the fly-by-wire aircraft system used for research is flown by the evaluation pilot seated at the

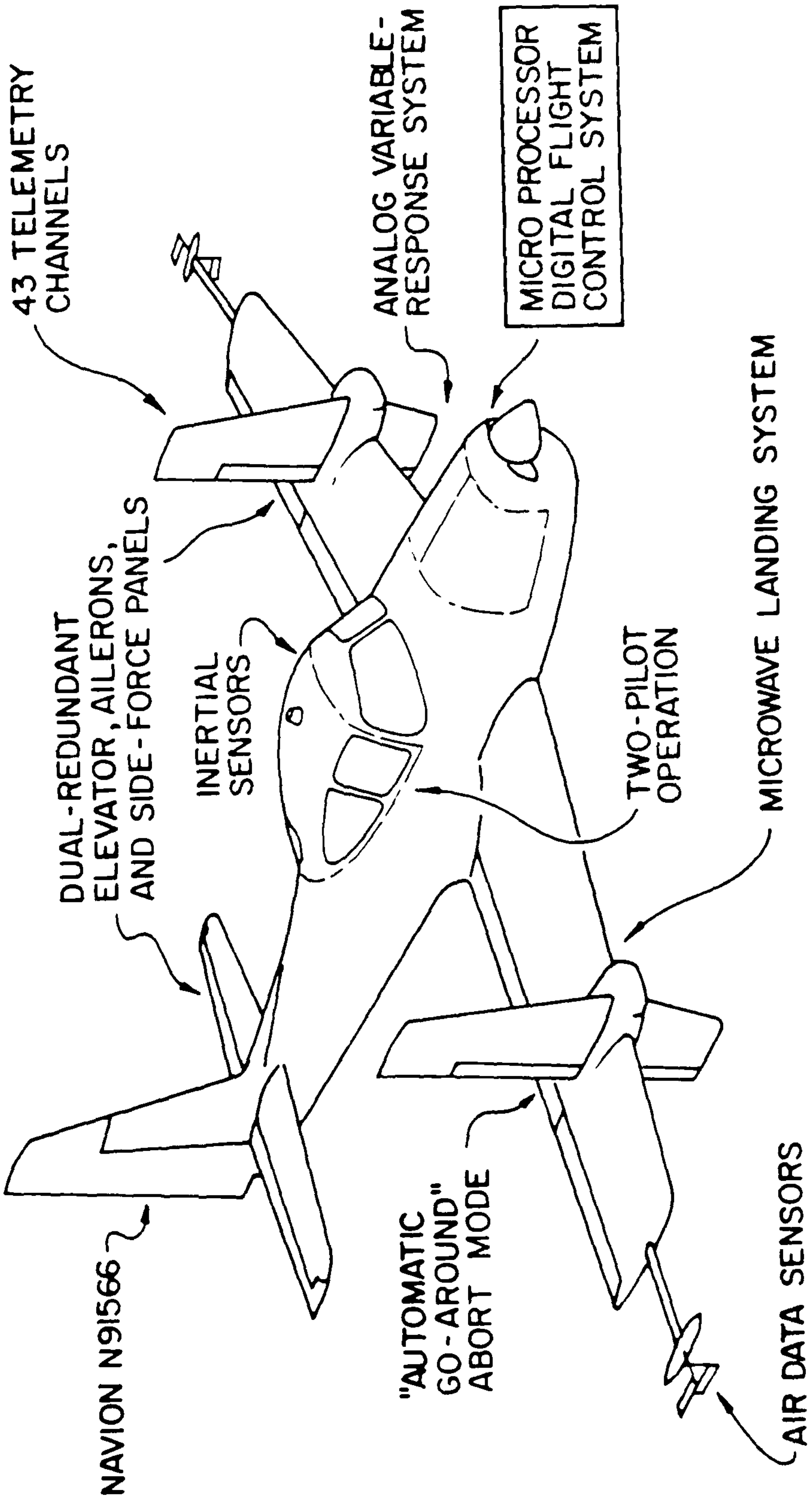

Figure A.2. Major Components of the VRA.

TABLE A.1

VRA Control Characteristics

Control	Displacement Limit, deg	Rate Limit deg/sec	Bandwidth Hz	Maximum Specific Force or Moment (IAS = 70kt)
Roll	30.0	70.0	5 (10)	4.1 rad/sec^2
Pitch	-30.0 +10.0	70.0	5 (10)	4.4 rad/sec^2
Yaw	15.0	70.0	5 (10)	1.9 rad/sec^2
Thrust	-	-	0.6	0.1 g
Side Force	35.0	60.0	2 (3)	0.25 g
Normal Force	30.0	110.0	2 (3)	0.5 g

right. This system includes the Micro-DFCS and redundant aileron, elevator, and side-force actuators for protection against system failures. The evaluation pilot's station is tailored to the experiment; for the longitudinal flying qualities program, this station includes a center control stick, rudder pedals, angle-of-attack indexer, and conventional instruments.

The safety pilot is the in-flight test conductor, monitoring systems and adjusting all experimental parameters. He has several electrical and hydraulic mechanisms for disengaging the Micro-DFCS and the variable-response system in the event of a malfunction, as well as an "automatic go-around" abort mode which makes safe experimentation through touchdown possible. The abort mode commands a 20-deg flap

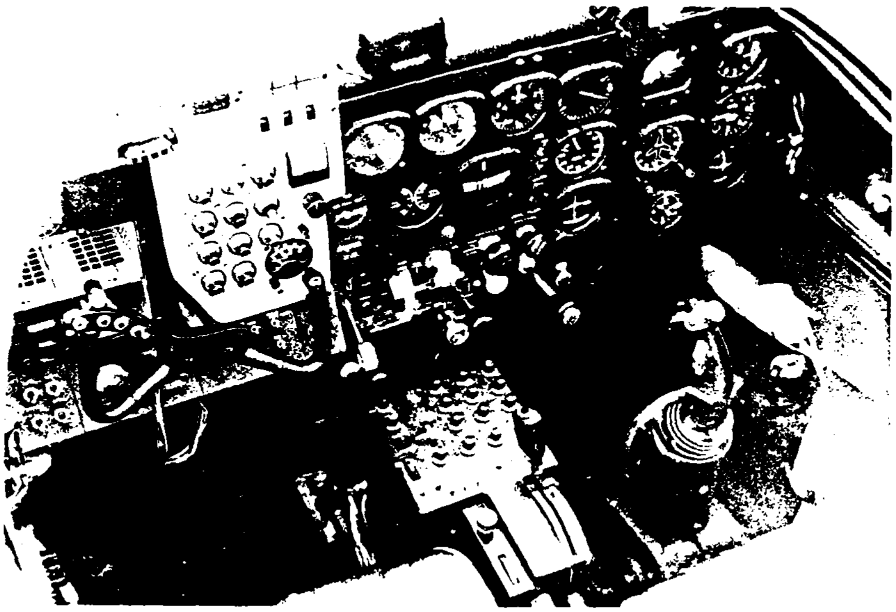

Figure A.3. Instrument Panel and Controls of VRA.

setting and climb power when activated; at 70 kt (36 m/s) airspeed on a 6 deg glideslope, an up-flap "hardover" failure can be corrected and climbout can be initiated with a maximum altitude loss of 10 ft (3 m). The landing gear can be adjusted to withstand rates of descent at touchdown of up to 12 f/s.

A.2 EXPERIMENTAL FACILITIES

The VRA is operated from the flight test facility at Princeton University's James Forrestal Campus. The facility includes the FRL hangar, laboratories, and shops, plus a 3000-ft Basic Utility II runway. A US Navy Field Carrier Landing Practice (FCLP) mirror, and TALAR 3 and 4 fixed-beam microwave landing systems (MLS) can furnish precision approach-path guidance.

The ground station (Figure A.4) at the FRL is used to receive, record, and analyze the telemetered data from the VRA. It includes a Honeywell 7600 fourteen-channel tape recorder, an FM or AM receiver presently operating at 1458 MHz in the FM mode, a PDM telemetry demultiplexer with five translators, an EAI TR-48 analog computer, a radio telephone, an Offner six-channel thermal paper strip chart recorder, and an eight-channel microcomputer-based Telemetry Monitoring system. The PDM telemetry system provides 42 data channels, each sampled at a rate of 20 sps. The telemetry data from the receiver can be recorded on tape or on 8.5 inch floppy disks and demultiplexed 6 channels at a time for plotting on the strip chart recorder. The analog computer scales and buffers all input channels from the TM system to the strip chart recorder.

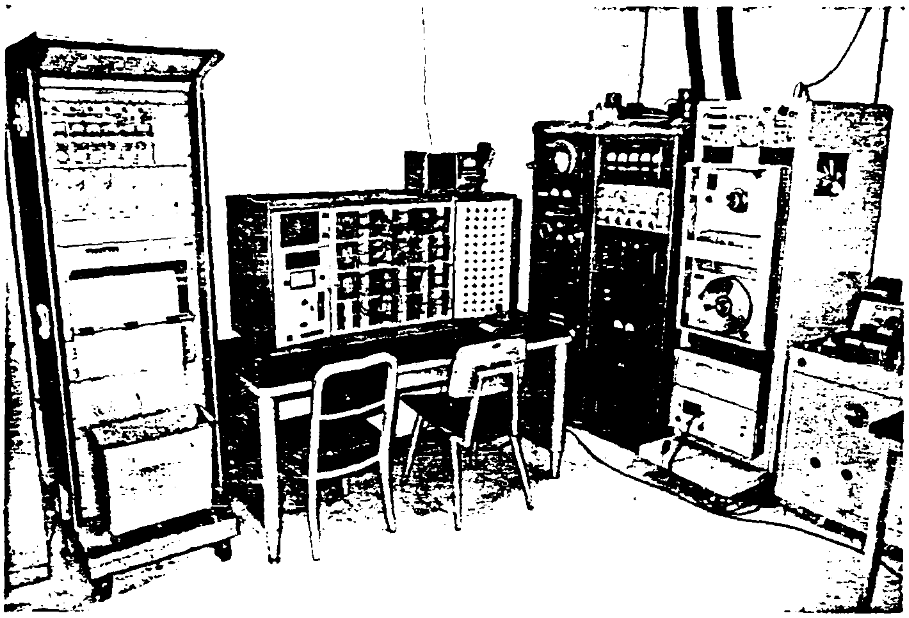

Figure A.4. FRL Ground Station.

In addition to the analog computer's function in analyzing telemetered data, it is also used for ground-based simulations of the VRA and other dynamic systems. In the longitudinal flying qualities study, it is used to model the base and equivalent aircraft configurations for ground testing the microcomputer software. The schematic diagram and corresponding potentiometer settings are presented in Fig. A.5 and Table A.2, respectively.

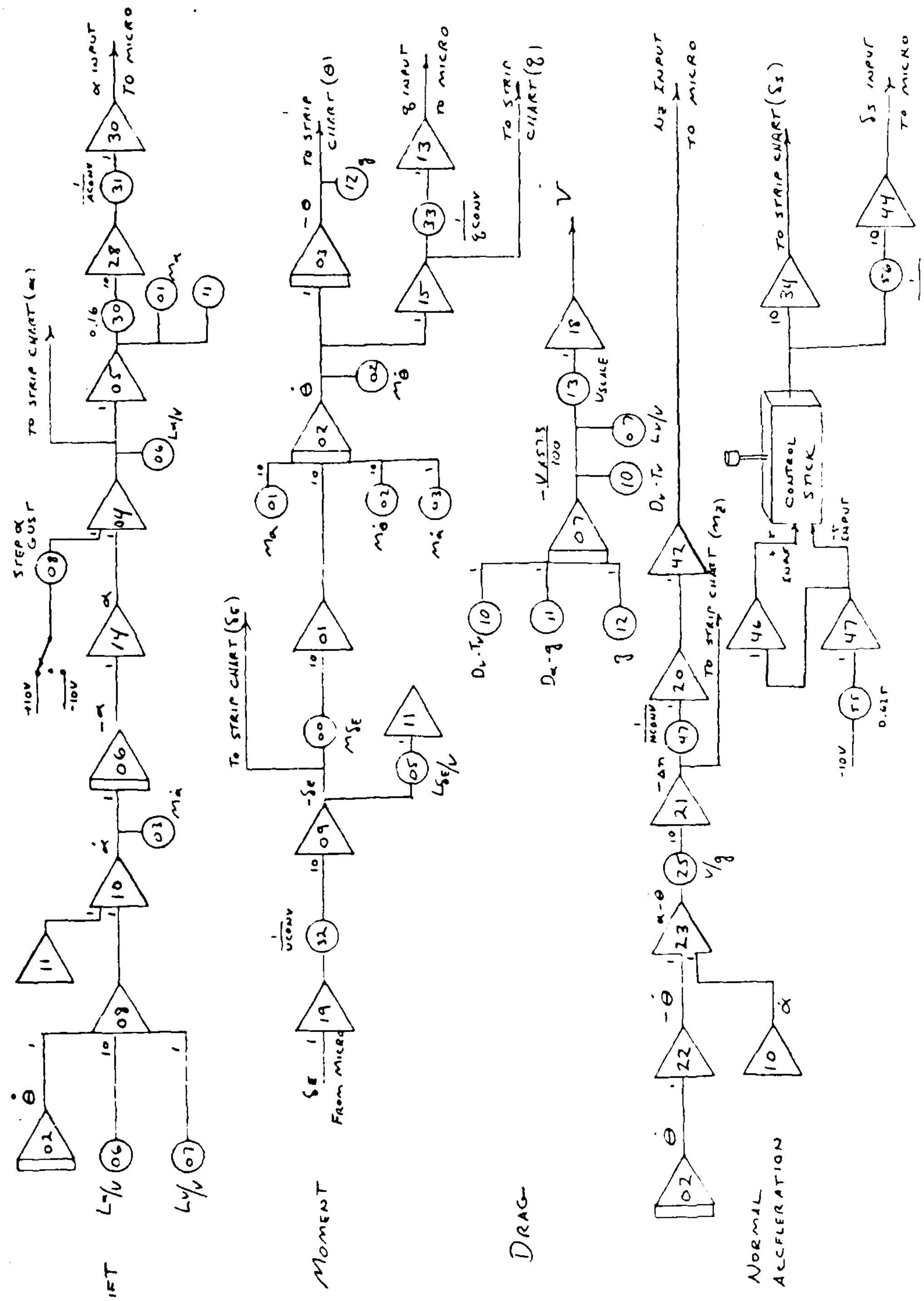

Figure A.5. Schematic of Simulated Base and Equivalent Configurations.

TABLE A.2

Analog Computer Potentiometer Settings

Pot	Parameter	Scaling	Setting
00	L_α/V	$L_\alpha/V/10$	Variable
01	M_α	$M_\alpha/10$	Variable
02	M_q	$M_q/10$	Variable
03	$M_{\dot\alpha}$	$M_{\dot\alpha}$	.880
05	stick scaling		.021
06	stick bias		.000
15	$M_{\delta E}$	$M_{\delta E}/100$	.099
17	$L_{\delta E}/V$	$L_{\delta E}/V$	.089
20	S scaling		.134
30	D_V-T_V	D_V-T_V	.100
31	$D_\alpha-g$	$L_\alpha-g/100$	.200
32	g	$g/100$	.322
33	L_V/V	$100 \times L_V/V$	.420
36	V/g	$V \times 20/g \times 57.3$	.136
38	V scaling		.348
45	n/volt	1v = .05g	.305
46	$\dot\theta$/volt	1v = 1°/sec	.984
47	/volt	1v = 1°	.377
50	ϵ/volt	1v = 1°	.148

Variable settings are shown in Table 3.1.

A.3 FRL MICROCOMPUTER SYSTEMS

Two microcomputer systems were involved in the development and application of the pCAS flight control program. The first is the FRL Ground Station Microcomputer, which is used for program development and for ground support during operations; and the second is the Microcomputer-based Digital Flight Control System.

A.3.1 FRL Ground Station Microcomputer

The Ground Station Microcomputer consists of a Monolithic Systems Corp. 8009 single- board computer, a card cage, two SMS floppy-disk drives, a Lear-Siegler ADM-31 terminal and an Anadex 9501 line printer. The 8009 board, card cage, and disk drives are mounted, with their power supply, in a cabinet which also houses the Flight Research Lab's Telemetry Monitoring system. The setup is shown in Fig. A.6 .

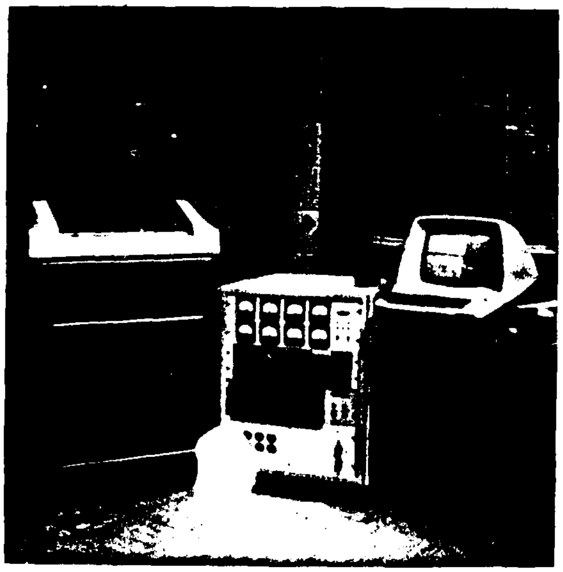

Figure A.6. 8009 Disk System .

Appendix B

PILOT RATINGS AND COMMENTS

This appendix includes ratings and comments transcribed from comment cards which the evaluation pilots were requested to fill out for each configuration flight test. Comments relate to the twelve categories listed below.

PILOT COMMENT CARD

1. PITCH ATTITUDE RESPONSE
   - initial response (delays?)
   - predictability of final response
   - special pilot techniques?
   - *PIO tendency? (hi/lo frequency)*
2. FLIGHT PATH RESPONSE
   - response time
   - predictaability of flight path
   - meatball tracking
   - flare/landing
3. AIRSPEED CONTROL
4. PERFORMANCE ASSESSMENT
   - meatball
   - flare/landing
   - special techniques?
5. CONTROL FEEL
   - forces, displacements
   - pitch sensitivity, trim?
6. TURBULENCE/WIND A FACTOR?
7. LATERAL-DIRECTIONAL CHARACTERISTICS A FACTOR?
8. MAJOR PROBLEMS
9. PIC RATING

10. APPROACH/MEATBALL RATING

11. FLARE/LANDINC RATING

12. ADDITIONAL COMMENTS

PILOT A COMMENTS

config comments

01 1-loose resp, fair pred, easy tech; 2-slow/fair resp, fair pred, fair ball, fair land; 3-poor; 4-poor/fair ball, poor/fair land; 5-OK; 8-bit loose in pitch, heave slow, hard to see over nose; 10-4; 11-4 1/2;

01 1-sluggish resp, fair pred; 2-slow resp in close, OK pred, ball, land; 3-OK; 4-fair ball, land; 10-3; 11-3 3/4; 12-in close meatball a bit slow, use more pitch than desired, then slip on angle of attack and IAS but OK;

02 1-soft resp, OK pred, in close high freq PIO; 2-slow resp, fair pred, ball, land; 3-varied; 4-OK ball, poor (long) land; 5-OK; 8-soft heave, slow pitch response, PIO tendency in close; 10-4 1/4; 11-5 1/4; 12-a bit sloppy in pitch and soft in heave, gives divergance at ramp, either hard or long touchdown;

03 1-OK resp, pred; 2-good resp, excellent pred, ball, good land; 4-fair/good ball, good land; 5-little stiff forces, need trim; 10-3; 11-3;

03 1-OK resp, pred; 2-slow resp at ramp, OK pred; 4-OK ball, bit hard land; 10-3 1/2; 11-4 1/2;

04 1-quick hard resp, excellent pred; 2-slow resp, poor pred, ball, land; 3-OK; 4-poor ball, land; 5-stiff forces, need trim; 6-a bit (high gain); 8-slow heave on final, lot of trim needed to get airspeed; 9-(no PIO) 2; 10-5; 11-5;

05 1-sloppy resp, pred, lead required; 2-slow resp, fair pred, ball, land; 3-OK; 4-fair ball, OK land; 5-OK; 8-slow ball response; 10-4; 11-4;

06 1-quick resp, fair pred, careful tech in pitch control; 2-quick resp, good pred, ball, land; 3-good; 4-good; 5-OK; 8-bouncy but OK; 10-3 1/2; 11-3;

07 1-OK resp, fair pred; 2-good resp, pred, fair ball, OK land; 3-bit loose; 4-fair ball, OK land; 5-OK; 8-loose in pitch; 10-4; 11-3;

07 1-OK resp; 2-good resp, pred, OK ball, land; 4-OK ball, land a bit high and long; 6-a bit; 7-turb upset; 10-2 3/4; 11-3 1/4; 12- good positive response, holds trim, lands as desired;

11 1-resp bit slow, poor pred, lead required, slt hi freq PIO; 2-slow resp, fair pred, ball, poor land;

3-OK/poor; 4-fair ball, poor land, lead for PIO; 5-OK; 8-lagging pitch response in close and touchdown, airspeed varied in run 2; 10-4 1/2; 11-4 1/2;

12 1-slow resp DELAY, poor pred, slt PIO in close; 2-slow resp, fair pred, ball, poor land; 3-fair varied; 4-fair ball, poor (long) land; 5-OK; 6-a bit; 8-delay or sluggish pitch response; 9-4; 10-4 1/4; 11-5 1/4; 12-don't trust pitch heave response so try to use more power variations to hold ball, even in close hard work;

13 1-bit slow resp, fair pred, lead required; 2-slow resp, fair pred, poor ball, land; 3-trim a problem; 4-poor ball, very poor land, lead required; 5-stiff forces, need trim; 6-a bit (high gain); 8-heave control; 9-3 (slow meatball cycle); 10-6; 11-7; 12-very poor flare response;

22 1-fair resp, OK pred; 2-sluggish resp, poor pred, ball, fair land; 3-poor; 4-poor ball, fair land; 5-OK; 6-alittle annoying; 8-slow path response; 9-3 (long osc. on slope); 10-6 1/2; 11-7; 12-difficult to flare without bolting;

23 1-loose resp, fair pred, careful tech; 2-quick resp, good pred, ball, fair land; 3-poor fair (low at TD); 4-good ball, fair land; 8-slow on flare, hit hard, low airspeed, run 2 ballooned on attempted flare; 10-3 1/2; 11-4 3/4; 12-mismatch between pitch and heave response;

25 1-fair resp, pred; 2-slow resp, fair pred, poor/fair ball, OK land; 3-fair +/- 5 knots; 4-poor ball, OK land; 6-yes, moderate upsets; 8-turb, slow heave response; 9-3; 10-4 3/4; 11-4 3/4; 12-just a little too loose and sloppy in heave/pitch to control precisely at ramp/TD;

26 1-sloppy resp, fair pred, lower gain tech to stop PIO, high freq PIO; 2-good resp, fair pred, fair/poor ball, OK land; 3-fair; 4-poor ball, OK land, tryed to stop bouncing; 6-a bit; 8-bounces in pitch and heave; 9-5 1/2; 10-4; 11-4; 12-bouncy, but can be put where desired in pitch, gama, and flare;

27 1-sloppy resp, poor/fair pred, had to think; 2-slow resp, fair pred, ball, late land; 3-poor (high, varied); 4-fair ball, poor/fair land, lead required; 5-OK; 8-slight DELAY in flare, airspeed needs attention; 10-4 1/2; 11-4 1/2;

28 1-good; 2-excellent, good land; 3-fair/good; 4-excellent ball, good land; 5-OK; 6-yes, light to moderate upsets; 8-turbulence; 9-2; 10-3; 11-3 1/4; 12-nic considering turbulence upsets;

31 1-slow soft resp, fair pred, careful tech;

2-poor/fair resp, fair pred, poor/fair ball, fair land; 3-vary alittle; 4-fair/good ball, fair land (long); 5-OK forces, hard to trim; 6-yes, moderate upsets; 8-turbulence keeps stirring the pot, loose (slow) response in pitch and flight path; 10-4 3/4; 11-4 3/4; 12-low heave response obvious in close;

32 1-slow resp DELAY, poor pred, lead reqired; 2-slow resp, fair pred, ball, slow uneasy land; 3-sloppy; 4-fair/poor, lead required; 5-OK; 10-5 1/4; 11-6; 12-low lift response with lag/delay in elevator gives poor ball in close and flared long;

33 1-large DELAY, poor pred, lead required, high freq PIO; 2-slow resp, poor pred, ball, land; 3-difficult; 4-fair ball, poor land, need smooth lead; 5-OK; 8-pitch delay; 9-5; 10-6; 11-7;

34 1-good; 2-good, fair land; 3-OK; 4-good ball, fair land (hard), lead required; 8-LAG on flare led to hard landing; 9-3; 10-3; 11-4; 12-OK except for late flare;

35 1-slow resp, slt DELAY, OK pred; 2-good, fair land; 3-OK; 4-good ball, fair land; 5-OK; 6-overflare on TD due to late pitch response, run 2 flared OK with a little lead; 9-2; 10-3 3/4; 11-4 1/4; 12-good airplane in smooth air;

36 1-DELAY, OK pred, lead required; 2-good, fair land; 3-OK; 4-good ball, fair land (long), lead flare point; 5-OK; 8-delay in pitch requires lead in flare; 9-2; 10-4; 11-4 1/4; 12-very smooth air, posed little problem even with noticeable delay;

PILOT B COMMENTS

{comments not available at this time}

PILOT C COMMENTS

config comments

01 1-slt DELAY, good pred, need to anticipate, slt low freq PIO; 2-OK pred out far, good ball, OK land; 5-OK; 10-2; 11-4;

01 2-OK; 3-slt difficulty; 10-2; 11-3;

01 2-good resp, very pred; 4-good; 8-pitch/bigger nose movements; 10-2; 11-3;

02 1-sluggish resp; 2-bigger stick inputs; 3-OK; 5-larger forces; 8-numerous inputs; 9-very slt PIO; 10-3; 11-4;

03 5-"heavier" bigger inputs required; 10-2; 11-3; 12-less responsive, well damped;

03 1-predictable; 2-quick resp, good pred; 5-small inputs, easy to make; 10-2; 11-2;

04 1-quick resp, good pred; 5-small inputs, sensitive; 8-sensitive; 10-2; 11-3;

05 1-good; 2-slt slow resp, very good pred, OK ball, land; 3-good; 4-good easy ball, larger stick inputs; 5-larger forces; 10-3; 11-3;

06 1-quick resp, slt hi freq PIO; 2-quick resp, OK pred, ball; 4-OK land; 5-light good forces; 6-yes; 8-windup; 10-4; 11-7; 12-slight PIO in turbulence;

06 1-slt LAG; 2-very pred, good land; 3-good; 5-OK; 10-2; 11-2; 12-very responsive;

07 1-slt DELAY; 6-thermals; 10-2; 11-3;

07 5-larger forces; 10-2 1/2; 11-3; 12-no heaving;

07 10-2; 11-2 1/2; 12-quick, responsive with small inputs;

07 4-good; 10-2; 11-3; 12-quick, predictable;

11 1-LAG, unpred, high freq PIO in close; 3-small problem; 8-unable to land without PIO; 10-5; 11-8;

11 1-slt DELAY; 2-less pred; 5-bigger displacements; 8-don't make big corrections; 10-4; 11-5;

12 1-noticable LAG, OK pred, low freq PIO; 2-easy pred out far, OK ball but slight overdrive, precise land difficult; 3-OK; 4-OK ball far out; 5-good; 8-Lag in close, loss of predictaability; 9-susept. in close; 10-4; 11-6;

12 4-sltly bigger/longer inputs; 5-bigger displacement, less sensitivity; 8-corrections difficult; 10-3; 11-4; 12-quick/precise;

13 1-slt DELAY; 4-longer inputs, high land; 10-2; 11-3;

22 1-LAG; 10-3; 11-4; 12-slt loss of predictability in close;

23 1-sluggish resp, good pred; 2-very pred; 3-good; 5-sltly larger; 10-2; 11-3; 12-single inputs satisfactory;

23 1-good pred; 2-quick resp, OK pred; 3-OK; 6-thermals; 10-2; 11-3; 12-slight heave;

23 1-LAG, low freq PIO; 8-lead corrections, multiple corrections; 10-5; 11-6; 12-low pred on landing;

25 1-low freq PIO; 2-LAG (small), bad pred; 8-big pitch input changes for desired response; 10-4; 11-6; 12-large inputs in close;

25 1-sluggish resp; 8-settled with aft stick at ramp; 10-3; 11-5; 12-little flight path response to aft stick inputs;

26 1-high freq PIO; 2-LAG, difficult pred; 8-control LAG caused loss of predictability; 9-suscep. PIO on landing; 10-4; 11-8; 12-didn't touch down due to PIO.

26 1-LAG, PIO; 8-unable to make small precise inputs; 10-5; 11-6; 12-trouble setting attitude;

26 1-slt LAG/DELAY, low freq PIO; 6-slt thermals; 8-chasing corrections in close; 10-3; 11-4; 12-loss of predictability in precise corrections;

27 1-slt LAG, very slt low freq PIO; 2-slt slow resp, good pred; 3-OK; 5-good; 10-2; 11-4; 12-no lead and counters;

27 5-OK; 10-2; 11-3;

27 1- fairly quick resp, slt high freq PIO; 8-many inputs chasing; 10-4; 11-5 1/2; 12-bobbles;

28 1-slt delay; 8-LAG; 10-3; 11-4; 12-slt loss of predictability;

31 1-slt DELAY, OK pred; 2-good pred; 3-hard; 4-slt anticipation needed; 5-OK; 10-2; 11-3;

31 1-small LAG, loss of pred in close; 4-ball OK with small corrections; 8-unable to make quick corrections in close; 10-4; 11-6; 12-little bobbles;

32 1-slt DELAY, slt PIO; 10-2 1/2; 11-4 1/2; 12-more nose movement;

33 1-noticeable DELAY, high freq PIO; 2-OK pred; 8-PIO in close; 10-3; 11-5; 12-exciteable short period;

33 1-LAG, loss of pred; 8-cannot make quick fine corrections in close; 10-4; 11-6; 12-needs small inputs; always behind;

34 1-quick resp, good pred, maybe PIO; 2-good pred; 3-OK; 5-sltly bigger forces; 6-thermals; 10-2; 11-3;

35 3-OK; 5-larger forces; 6-slt thermals; 8-bigger inputs; 10-2; 11-3;

35 1-good resp; 3-OK; 5-good; 10-2; 11-3;

36 1-slt DELAY; 6-thermals; 10-2; 11-4

36 1-LAG, low freq PIO; 8-LAG hurt in close corrections; 10-3; 11-5; 12-PIO in close;

PILOT D COMMENTS

config comments

01 1-good resp; 2-good; 10-3; 11-4; 12-large throttle movements;

01 1-good resp; 3-minor deviations; 6-turb; 10-4; 11-4; 12-good ball control

01 1-quick resp; 4-small inputs; 6-turb; 10-3; 11-4; 12-freq increased at ramp;

01 1-good resp; 2-good ball; 4-small inputs; 10-3; 11-4; 12-at range small infreq inputs, in close small but more freq;

02 2-sluggish resp; 3-real problem; 10-5; 11-5; 12-long time for correction to take effect;

02 1-good resp; 3-minor deviations; 6-lateral gusts; 8-alittle sluggish; 10-3; 11-4; 12-corrections easy to make;

03 1-good resp; 2-good resp; 4-small inputs; 10-2; 11-3; 12-pitch capture no problem;

03 1-good resp; 2-good resp; 3-good; 4-small inputs required; 10-2; 11-3; 12-nose movement right away;

03 1-sluggish resp; 2-good resp; 10-3; 11-4;

04 1-quick resp; 4-freq inputs; 10-3; 11-3; 12-pitch capture no problem;

04 1-good resp; 3-good; 4-freq small inputs at range, larger at ramp, sensitive; 8-minor but annoying degraded flight path control; 10-4; 11-5;

05 1-good resp; 3-adequate; 4-small inputs; 10-3; 11-3;

06 1-good resp; 2-good pred; 3-good; 4-small but numerous inputs; 10-4; 11-4; 12-quick and well-damped short period;

07 1-sluggish pitch; 3-good; 10-2; 11-4; 12-positve feel;

07 3-good; 10-2; 11-3;

07 1-good resp; 4-small inputs required; 10-3; 11-3;

11 1-good resp, PIO tendency on pitch capture; 4- pitch

resp not adequate at ramp; 8-easy to get low and slow; 10-4; 11-7; 12-felt like could control PIO at end;

12 1-good resp; 3-adequate; 4-larger long inputs at range, small inputs for ball control; 8-touble maintaining precise nose attitude; 10-4; 11-5;

13 1-deviations; 8-tended to overcontrol pitch attitude, large pitch attitude for small flight path change; 10-4; 11-5;

22 3-hard to maintain; 4-long stick inputs; 8-PIO tendency; 10-5; 11-7;

23 1-quick resp, too quick; 3-good; 4-small inputs at range and large in close; 8-tendency to overcontrol pitch; 10-4; 11-6;

25 1-good resp but LAG; 3-good; 10-4; 11-6; 12-healthy nose movements;

26 1-LAG, high freq PIO; 3-OK; 8-overcontrol ball movement; 10-4; 11-7;

26 10-4; 11-7;

26 1-sluggish resp; 10-5; 11-7; 12-tendency to overcontrol;

27 10-3; 11-6; 12-large throttle inputs, problem with lift curve slope;

28 1-resp sluggish, good DELAY; 3-good; 4-large inputs; 5-large forces; 10-3; 11-5; 12-kept ball in limits;

31 1-quick resp, bit of LAG, PIO at ramp; 8-had trouble on pitch capture; 10-5; 11-7; 12-tendency to overcontrol;

31 1-good resp, slt DELAY; 4-numerous large inputs; 6-turb; 8-working pretty hard; 10-5; 11-7; 12-overcontrols;

32 1-LAG; 8-fighting it whole time; 10-6; 11-6;

32 3-slt; 4-large power and stick to compensate; 10-6; 11-6; 12-not very predictable;

32 1-good resp, DELAY; 4-large inputs; 6-turb; 8-working hard; 10-5; 11-6;

33 1-good resp, large DELAY, PIO in close; 8-delay caused real problems at range and in close; 10-6; 11-7;

33 1-large DELAY; 6-turb; 8-overcontrols; 10-6; 11-7; 12-being smooth didn't help;

34 1-sluggish resp, slt LAG; 4-large inputs and freq; 10-3; 11-5; 12-lag no problem at range;

35 1-lag felt at range hurt in close; 10-3; 11-7; 12-went alittle low, attempt to correct caused a large overcontrol;

36 1-gradual increase in LAG; 10-4; 11-6; 12-at range corrections increasing;

PILOT E COMMENTS

config comments

01 1-good pred, slt low freq PIO; 2-good pred; 4-easy to overcontrol; 10-5; 12-pitch capture -- 3-4 inputs, nose overshoots;

02 1-good pred; 2-fair/good resp, good pred, ball; 10-2; 12-pitch capture -- 1 overshoot, 1 stick counter;

03 1-sensitive, sluggish resp; 2-good; 4-more stick than necessary; 5-sltly heavy; 8-more stick force and deflection required for nose up; 10-3 1/2; 12-pitch capture 10 degrees +/- 2 degrees;

04 1-good pred; 2-after initial movement a little sluggish to capture pitch angle; 4-tough to flare; 5-initially sensitive; 10-3; 12-initially sensitive, then sluggish, undershoot angle;

05 1-sensitive, good pred,slt PIO; 10-3; 12-pitch capture : 2 overshoots;

05 1-good pred; 2-good; 3-varied; 4-predictable nose resp; 5-initially sensitive; 10-2;

06 1-quick resp, good pred, slt PIO; 2-quick resp, good pred; 3-fair; 5-sensitive; 10-3; 12-pitch capture: 2 overshoots;

07 1-good pred; 2-good resp; 4-good land, slt overcontrol; 5-good, initially sensitive; 10-2;

11 1-overcontrol, moderate PIO; 2-quick resp; 10-4 1/4; 12-pitch capture: 4 stick movements;

11 1-large DELAY, poor pred, large PIO; 2-good resp, good pred, poor land; 10-7; 12-pitch capture: gross overshoot, 4-5 stick movements 1-2", 3-4 nose transients;

12 1-sluggish resp, fair pred, slt medium freq PIO; 2-fair; 8-tracking task difficult; 10-5; 2-pitch capture: sluggish response causes overshoot, 1-2 stick inputs;

13 1-less sensitive, good pred; 2-good; 5-sltly higher stick displacement/force but good response; 10-2;

13 1-large DELAY, good pred; 2-good resp; 8-bad down A/C appeared to float-tough to get nose over to get ball down; 10-4; 12-pitch capture: required more stick deflection and force to capture angle, no overshoots but undershoots by

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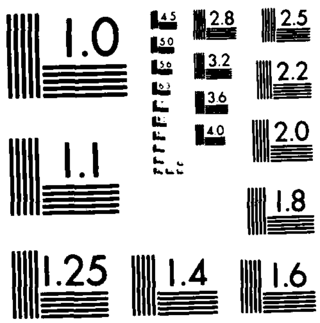

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

1-2 degrees;

22 1-slt DELAY, good pred; 2-good resp, good ball; 5-good; 10-3; 12-pitch capture: slt overshoot;

22 1-good pred; 8-A/C floated; 10-3; 12-pitch capture: appeared slower resp, more stick deflection and force required but good character;

23 1-DELAY, fair/poor pred, mod/strong PIO; 10-5; 12-pitch capture: 3-4 stick inputs and nose overshoots;

23 1-moderate DELAY, poor pred, low gain, medium freq PIO; 2-fair/good resp, good pred, fair ball, tough to flare; 10-5; 12-pitch capture: dig in and overshoot, 5 degrees and 3-4 stick pumps;

25 1-moderate DELAY, poor pred, easy [illegible] input, slt PIO; 2-nominal resp, fair ball; [illegible] initial overshoot great; 10-4 1/2; 12-pitch capture: [illegible] overshoots (1-2" stick), 3 nose bobbles;

26 1-slt DELAY, poor pred, low gain, moderate PIO; 2-good resp, fair pred, good ball; 5-max sensitivity; 8-pitch attitude overshoot gross; 10-6; 12-pitch capture: 4-5 stick inputs, 4 nose movements 5-7 degrees;

27 1-delays, very poor pred, low gain input, strong PIO tendency; 4-overcontrol; 10-6; 2-pitch capture: +/- 2 degrees, 4 stick inputs +/- 2-3" and4 nose overshoots;

27 1-poor pred, low gain, slt/mod PIO; 2-very poor resp; 5-sensitive; 10-5 1/2; 12-pitch capture: dig in and overshoot 5 degrees, 3-4 stick inputs;

28 1-slt DELAY, fair pred; 2-dig in tendency; 5-OK; 10-3; 12-pitch capture: slt LAG;

28 1-god pred; 2-good resp up fair down, good pred; 5-good; 10-2;

31 1-DELAY, poor pred, low gain input, moderate PIO; 2-slow resp, fair pred, sluggish ball, 8-major PIO in close trying to control nose attitude; 10-5; 12-pitch capture: 3" stick inputs, 3 nose attitude overshoots 2-3 degrees;

32 1-sensitive, poor pred, low gain input, strong medium freq PIO; 2-slow resp, poor pred, ball, land; 4-nose moves but ball does not; 5-sensitive; 8-PIO due to pitch changes when throttle moved, PIO when initiated flight response test; 10-7; 12-pitch capture: 4 stick inputs and nose overshoots +/- 5 degrees, almost divergant;

33 1-large DELAY, very poor pred, very low gain input,

max high freq PIO; 2-fair pred; 4-very tough; 8-tracking maneuver impossible due to divergant PIO; 10-8; 12-pitch capture: 5-6 stick inputs, 5-6 nose overshoots;

34 1-slt DELAY, fair pred, very slt high freq PIO; 5-very sensitive; 10-4; 12- pitch capture: tended to undershoot after initial good nose movement, took additional stick input to capture angle;

35 1-slt DELAY, fair/good pred; 2-very quick resp, good pred; 5-not sensitive; 10-3;

36 1-slt/mod DELAY, good pred, slt PIO; 2-good; 5-not very sensitive; 10-3; 12-pitch capture: slt overshoot, 1 stick pump;

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